A Survey of 3–5.4 μm Emission from Planetary Nebulae Using SOFIA/FLITECAM

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Abstract

Here we present the results of an airborne 3–5.4 μm spectroscopic study of three young, carbon-rich planetary nebulae (PNs) IC 5117, PNG 093.9-00.1, and BD +30 3639. These observations were made using the grism spectroscopy mode of the First Light Infrared TEst CAMera (FLITECAM) instrument during airborne science operations on board NASA’s Stratospheric Observatory for Infrared Astronomy (SOFIA). The goal of this study is to characterize the 3.3 and 5.25 μm polycyclic aromatic hydrocarbon (PAH) dust emission in PNs and study the evolution of PAH features within evolved stars before their incorporation into new stellar systems in star-forming regions. Targets were selected from Infrared Astronomical Satellite, Kuiper Airborne Observatory and Infrared Space Observatory source lists, and were previously observed with FLITECAM on the 3 m Shane telescope at Lick Observatory to allow direct comparison between the ground and airborne observations. We measure PAH emission equivalent width and central wavelength, classify the shape of the PAH emission, and determine the PAH/aliphatic ratio for each target. The 3.3 μm PAH emission feature is observed in all three objects. PNG 093.9-00.1 exhibits NGC 7027-like aliphatic emission in the 3.4–3.6 μm region while IC 5117 and BD +30 3639 exhibit less aliphatic structure. All three PNs additionally exhibit PAH emission at 5.25 μm.

Unified Astronomy Thesaurus concepts: Infrared astronomy (786); Planetary nebulae (1249); Polycyclic aromatic hydrocarbons (1280); Post-asymptotic giant branch stars (2121); Spectroscopy (1558); Infrared observatories (791)

1. Introduction

Due in part to their ubiquity, the broad infrared spectral features at 3.3, 6.2, 7.7, 8.6, 11.3, and 12.7 μm are an important focus of near and mid-infrared astronomy. Originally referred to as the unidentified infrared bands, through comparisons with laboratory data, they are generally attributed to the vibrational, bending and stretching modes of the C–H and C–C bonds in polycyclic aromatic hydrocarbons (PAHs; Gillett et al. 1975; Leger & Puget 1984; Sellgren 1984). PAHs are assemblies of benzene-ring-like structures, and include molecules such as pyrene, naphthalene, and coronene, which when excited by absorption of a UV photon, relax through emission in the infrared (van Dierenhoffen et al. 2004). These broad emission features have been observed in a wide range of astronomical objects, including planetary nebulae (PNs), H II regions, protostellar clouds, and star-forming galaxies (e.g., Hora et al. 2004; Peeters et al. 2004). This has led to several studies aimed at correlating PAH emission with physical properties of the observed region (e.g., Tokunaga et al. 1991; Roche et al. 1996b; van Dierenhoffen et al. 2004; Cohen & Barlow 2005). While the laboratory spectrum of individual PAHs is known, mixing makes identification of individual PAHs in astronomical environments extremely difficult (see Section II in Allamandola et al. 1989b), resulting in descriptions of overall PAH population characteristics and environmental variations rather than identification of specific PAHs (Peeters et al. 2002).

PAH formation is believed to occur in the last stages of evolution of carbon-rich low- and intermediate-mass stars. Smith & McLean (2008) and Roche et al. (1996b) used the 3.3 μm band to determine the minimum C/O abundance ratios for PAH emission. They found “cutoff” C/O abundance ratios of 0.65 ± 0.28 and 0.77 ± 0.5, respectively. Cohen & Barlow (2005) similarly used the 7 and 8 μm bands to find a C/O threshold ratio of 0.54 ± 0.3. This supports the hypothesis that carbon-rich PNs produce hydrocarbons including PAHs (see Section IV of Allamandola et al. 1989b).

The most prominent hydrocarbon band in the 3–5.5 μm region is a broad feature centered at 3.3 μm, which sits on top of an extended plateau of emission, extending from ~3.2 to ~3.6 μm (Maltseva et al. 2018, and references therein). In most PAH emitting objects this is accompanied by a weaker band of emission beginning at 3.4 μm and extending to nearly 3.6 μm. This feature is believed to arise from emission from the C–H stretching of aliphatics, chemical subgroups, which do not show the alternating double- and single-bond structure between carbon atoms that aromatic compounds exhibit (Duley & Williams 1981). Proposed carriers include aliphatic side-groups (such as methyl) attached to the outer carbon molecules of PAH assemblies (Duley & Williams 1981; Yang et al. 2017), and HnPAHs, hydrogenated PAH molecules with additional hydrogen molecules attached to the carbon ring (Bernstein et al. 1996). Comparison of 3 μm spectra to laboratory spectra of methyl-coronene (Joblin et al. 1996) and HnPAHs (Bernstein et al. 1996) support both the side-group and HnPAH models. Sloan et al. (1997) suggested a mixed chemistry involving both side-groups and HnPAHs could be responsible for the observed 3.4 μm emission in the Orion Bar. Detailed
experimental work on PAH emission in the 3 μm region has been published recently by Maltseva et al. (2018). These authors show that hydrogenated PAHs form an important fraction of the IR emission carriers in regions with an anomalously strong 3.2–3.6 μm plateau. For simplicity, in this paper we refer to the 3.4 μm complex that sits atop the 3.2–3.6 μm plateau as the “aliphatic feature” and the 3.3 μm complex that sits above the plateau as the “PAH feature.” In addition to the features in the 3.2–3.6 μm region, several studies have also noted the presence of PAH bands at 5.25 and 5.7 μm including on Kuiper Airborne Observatory (KAO; Allamandola et al. 1989a), with UKIRT (Roche et al. 1996a), and with Infrared Space Observatory (ISO; Boersma et al. 2009). These features have been observed in a small number of PNs (e.g., NGC 7027, PNG 093.9-00.1, and BD +30 3639 Roche et al. 1996a; Boersma et al. 2009), as well as objects like the Orion Bar (Boersma et al. 2009). Boersma et al. (2009) used observational, laboratory, and theoretical data to investigate this feature. They attributed the 5.25 and 5.7 μm emission to combinations of CH stretching and CH in-plane and out-of-plane bending modes and found that the 5.25 and 5.7 μm features preferentially arise from large, compact PAHs, rather than irregularly shaped molecules.

This study uses guaranteed time observations made using the Stratospheric Observatory for Infrared Astronomy (SOFIA) and the First Light Infrared TEst CAMera (FLITECAM) instrument to investigate the 3–5.41 μm spectra of three young, carbon-rich PNs. It has three purposes: investigate the properties of 3.3 μm PAH emission in these PNs by expanding the analysis performed by Roche et al. (1996b) and Cohen et al. (1989); examine the 3.4 μm aliphatic emission in these objects; and characterize any 5.25 μm PAH emission if detected.

Target selection, the FLITECAM grism mode, and the observations are all described in Section 2, data reduction methods are explained in Section 3, and results and discussion are presented in Section 4. Finally, conclusions are given in Section 5.

2. Observations

2.1. Target Selection

The three objects in this study (IC 5117, PNG 093.9-00.1, and BD +30 3639) are young, carbon-rich PNs with known 3.3 μm emission (Roche et al. 1996b; Sahai et al. 2011). Young PNs have only recently begun to exhibit the ionized shells of dust and gas lost during a star’s post-AGB phase. The central stars of young PNs tend to have lower effective temperatures than more evolved PNs (Sahai et al. 2011). Additionally, young PNs tend to be compact, with significant dust opacities (Kwok 1994). The study of young PNs allows astronomers to study post-AGB mass loss, to understand the dynamical forces, which shape nebular structure, and to investigate the initial stages of dust formation, all of which is made more difficult in older PNs, which can be affected by interactions with the ISM, the influence of the central star wind, and the effects of photoionization (Sahai et al. 2011).

BD +30 3639 is a bright, young PN with a spectral classification of [WC9] (Weidmann & Gamen 2011; Heller et al. 2018), and a central star temperature of ∼47,000 K (Leuenhagen et al. 1996). BD +30 3639 exhibits 3.3 μm and aliphatic emission as well as 5.25 μm emission (Allamandola et al. 1989a). IC 5117 is a very compact PN that exhibits bi-polar outflows, molecular hydrogen emission, and aliphatic emission in the 3.4 μm region (Kwok 1985; Cohen & Barlow 2005). Hyung et al. (2001) found an evolutionary age of ∼7000 yr for IC 5117. The central star of IC 5117 has been estimated to be ∼120,000 K (Hyung et al. 2001), substantially hotter than that in BD +30 3639. The high-temperature central star may explain why IC 5117 exhibits high-energy forbidden line emission (Hyung et al. 2001). PNG 093.9-00.1 (also called IRAS 21282+5050) is a young, low excitation PN with a [WC11] spectral type (Kwok et al. 1993; Meixner et al. 1993) and a ∼28,000 K central star (Leuenhagen & Hamann 1998). It exhibits an abnormally large infrared excess and multipolar morphology (Hsia et al. 2019). PNG 093.9-00.1 is believed to be evolutionarily younger than both IC 5117 and BD +30 3639, with an evolutionary age of ∼5000 yr (Shibata et al. 1989).

IC 5117, PNG 093.9-00.1, and BD +30 3639 have been previously observed with FLITECAM in a ground-based survey using the Shane 3 m telescope at Lick Observatory, Mt. Hamilton, CA (Smith & McLean 2008). The Smith & McLean (2008) survey measured the 3.3 μm PAH emission in all three targets, but atmospheric water vapor made examination of the 3.4 μm aliphatic feature difficult. Likewise, the 5.25 μm feature was unobservable from the ground. These three objects were selected for airborne observations because the strength of their PAH emission made them optimal targets for detection of aliphatic and 5.25 μm emission if present.

2.2. Instrumentation

Observations of all three objects were carried out with FLITECAM. FLITECAM is a 1–5.41 μm camera developed at the UCLA Infrared Laboratory under the leadership of Dr. Ian McLean for NASA’s SOFIA project (McLean et al. 2006). SOFIA is a modified Boeing 747-SP airplane with a 2.5 m f/19.6 bent-Cassegrain telescope operating at altitudes up to 45,000 ft and therefore above 99% of the atmosphere’s water vapor content (Waddell & Davidson 2002). Performance and technical details of the instrument are described in McLean et al. (2006). FLITECAM was commissioned on board SOFIA in 2015 (Logsdon et al. 2014, 2016; Smith et al. 2014), but because FLITECAM operates in the near-infrared (NIR), and because the f/17 optics of the Lick 3 m telescope provides a plate scale similar to that of SOFIA, FLITECAM was also commissioned in 2002 October at Lick Observatory in a ground-based configuration (Mainzer & McLean 2003). FLITECAM was retired from SOFIA operations in 2018.

FLITECAM utilizes large refractive optics to inscribe an ∼8′′ diameter field of view on a 1024 × 1024 InSb ALADDIN III detector with a plate scale of 0′′.475 per pixel. FLITECAM was designed as an imaging camera, but also has a suite of three grisms which allow for nearly full coverage of the 1–5.41 μm range at a resolution of R ~ 1300–1800. The instrument can be operated in either the up-looking position (Lick) or the horizontal position (SOFIA). Although these measurements were made in the FLITECAM-only mode, FLITECAM can be co-mounted with another SOFIA instrument, High-speed Imaging Photometer for Occultations to provide simultaneous coverage of the optical and NIR bands (Dunham et al. 2004, 2014; Logsdon et al. 2014).
FLITECAM features a dual filter wheel, which houses standard broadband filters, several narrowband filters plus a suite of three direct-ruled KRS-5 grisms and their appropriate order-sorting filters. Each grism can be used in one of three orders giving a total of nine settings to nearly cover the entire 1–5.41 μm region. The KRS-5 grisms provide a moderate resolution spectroscopy mode in conjunction with fixed slits of either 1″ or 2″ width and 60″ total length to yield resolving powers of R ~ 1800 and 1300 respectively (Smith & McLean 2006). See Table 1 for details of the FLITECAM grism mode. The 3–3.365 μm range was observed with the LM order sorting filter and the C grism. This combination is referred to as the LMC band. The 3.365–4.1 μm range was observed with the LM order sorting filter and the B grism, referred to as the LMB band. There is an overlap between the LMB data was chosen to fall at 3.365 μm to avoid both the 3.3 μm feature peak, and continuing to 3.4 μm. The transition between LMC and LMB data was chosen to fall at 3.365 μm to avoid both the 3.3 and 3.4 μm features. The 4.4–5.41 μm range was observed with the LM order sorting filter and the A grism. This is referred to as the LMA band.

2.3. Observations

Observations were obtained over the course of three separate observing flights on board SOFIA in 2016 October. Spectroscopic observations were made in a standard ABBA nod pattern. Individual exposures ranged from 30 to 80 s per observation, depending on target and wavelength band. The object was nodded between two positions, designated A and B, separated by ~20″ on the ~60″ long entrance slit of FLITECAM. Signal-to-noise ratios (S/Ns) were typically greater than 10 (10%) per resolution element. Seeing conditions were ~2″/0–3″/0 and a slit width of 2″/0 (~4 pixels) was used for all observations. Each object was observed in at least three grism modes, providing coverage from ~2.8 to 5.41 μm, except for the 4.2–4.4 μm region, which is opaque even at SOFIA altitudes. PNG 093.9–00.1 was additionally observed in the 1.8–2.4 μm band. Standard infrared stellar calibrators were observed for wavelength and flux calibration. A summary of all observations can be found in Table 2.

3. Data Reduction

Data from all three objects was reduced using REDUX, SOFIA’s facility pipeline version 1.2.0 (Clarke et al. 2015). REDUX used the FSpextool software package, a version of the NASA Infrared Telescope Facility’s SpeX instrument data reduction software, Spextool (Cushing et al. 2004), that was specifically optimized for FLITECAM to extract, flat-field, and linearize the FLITECAM spectra (Cushing et al. 2004; Vacca et al. 2004; Clarke et al. 2015). For more detail see the FLITECAM Guest Observer (GO) Data Handbook.

Because SOFIA data were still subject to telluric contamination, our NIR spectra needed to be corrected for atmospheric, as well as instrumental effects. FSpextool achieved this by applying the standard ground-based NIR astronomy correction approach, that is by observations of a telluric standard star, generally an A0V star (Vacca et al. 2003). The corrected standard star spectra was reduced in the same manner as the science target data, then compared to a scaled Vega model to create a correction curve. In ground-based astronomy telluric standards and science targets usually have been observed at similar airmasses, but due to the unique operational aspects of

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**Table 1**

| Grism | Lines/mm | Order | OSF | Lambda start (μm) | Lambda central (μm) | Lambda end (μm) | Measured R |
|-------|----------|-------|-----|-------------------|---------------------|------------------|-----------|
| A     | 162.75   | 1     | LM  | 4.395             | 4.96                | 5.533            | 1680      |
| A     | 162.75   | 2     | Klong | 2.216             | 2.5                 | 2.784            | 1690      |
| A     | 162.75   | 3     | Hwide | 1.497             | 1.69                | 1.877            | 1710      |
| B     | 217      | 1     | LM  | 3.307             | 3.73                | 4.16             | 1780      |
| B     | 217      | 2     | Hwide | 1.649             | 1.86                | 2.076            | 1750      |
| B     | 217      | 3     | J    | 1.14              | 1.28                | 1.424            | 1720      |
| C     | 130.2    | 2     | LM  | 2.756             | 3.11                | 3.467            | 1670      |
| C     | 130.2    | 3     | Kwide | 1.872             | 2.11                | 2.346            | 1650      |
| C     | 130.2    | 4     | H    | 1.445             | 1.62                | 1.801            | 1640      |

**Note.** See Logsdon et al. (2016) and Smith & McLean (2006) for more details. Resolution measured for 2″ slit. LMA resolution determined from in-flight observations, other spectral resolutions determined at Lick Observatory.

**Table 2**

| Object Name | Spectral Type | T\(_\text{eff}\) (K) | Size (FWHM) (arcsec) | Obs Date | 3–3.4 μm Time (s) | 3.4–4.1 μm Time (s) | 4.4–5.41 μm Time (s) |
|-------------|---------------|---------------------|---------------------|----------|------------------|---------------------|----------------------|
| BD +30 3639 | [WC9]         | 47000               | 5.15                | 2016 Oct 14 | 360              | 360                 | 900                  |
| IC 5117     | [WR]          | 120000              | 2.95                | 2006 Oct 19 | 960              | 1440                | 960                  |
| PNG093.9–00.1 | [WC11]    | 28000               | 3.96                | 2016 Oct 20 | 480              | 720                 | 600                  |

**Note.** Spectral types from Weidmann & Gamen (2011). T\(_\text{eff}\) from BD +303639: Leuenhagen et al. (1996), IC 5117: Hyung et al. (2001), and PNG093.9–00.1: Leuenhagen & Hamann (1998). Angular size from FLITECAM K-band images.
airborne observations, this was not always possible on SOFIA. The effects of this airmass mismatch were removed by computing the appropriate telluric absorption model spectra for both the telluric standard and the target using the ATRAN code (Lord 1992), then re-binning the computed model spectra to match FLITECAM’s spectral resolution. The final telluric correction curve was calculated from the ratios of the telluric calibrator’s computed telluric model spectrum to the science target’s computed telluric model spectrum. This final correction curve was then applied to the science spectrum to produce a flux-calibrated, telluric corrected spectrum of the target (Vacca et al. 2015).

4. Results and Discussion

4.1. Overview

The 3.0–4.0 μm and 4.5–5.41 μm spectra for each object are presented in Figures 1 (BD +30 3639), 2 (IC 5117), and 3 (PNG 093.9-00.1). The difficulty of positioning the slit exactly in the same place on an extended object accounts for the slight mismatch in continuum levels from one grism observation to the next. The S/N for the 4.5–5.41 μm region was lower than the 3 μm regime due to atmospheric and thermal backgrounds, so data were smoothed using a 5 pixel wide Gaussian filter, which reduced the spectral resolution to ~700 in the 4.2–5.4
region. Atomic line emission from hydrogen was apparent in IC 5117 and BD +30 3639, with a tentative detection of Brackett-alpha emission in PNG 093.9-00.1. Additionally, IC 5117 showed [Mg IV] emission. See Table 3.

As expected, all three objects exhibit the 3.2–3.6 μm plateau, with the 3.3 μm PAH complex and the 3.4 μm aliphatic complex emission evident above the 3.2–3.6 μm plateau. In PNG 093.9-00.1 and BD +30 3639 we also clearly detected the PAH feature at 5.25 μm. Although weaker, this feature was also detected in IC 5117. The 5.7 μm feature associated with 5.25 μm emission is beyond FLITECAM’s wavelength range.

Before analyzing the 3.3 μm PAH feature, we smoothed the spectra with a five-pixel wide Gaussian filter and fit the Pfund-δ hydrogen emission line at 3.296 μm, which overlaps with the peak of the expected 3.3 μm PAH feature, with a Gaussian. The Pfund-δ feature was removed using IDL’s Gaussfit routines and MPFIT (Markwardt 2009).\textsuperscript{10} The continuum for the 3.3 and 3.4 μm features was fit using polyfit, with continuum points at 3.0 μm ± 0.025 μm and 3.8 μm ± 0.025 μm. We then calculated the equivalent width and flux of each feature. Using MPFIT and a modified version of XGAUSSFIT (Lindler 2001) we fit the 3.4 μm aliphatic feature with four overlapping

\begin{table}[h]
\centering
\begin{tabular}{|l|l|l|l|l|l|}
\hline
Object Name & Pfund-α Flux & Pfund-δ Flux & Pfund-γ Flux & Brackett-α Flux & Pfund-β Flux \\
& \((10^{-15} \text{ W m}^{-2})\) & \((10^{-15} \text{ W m}^{-2})\) & \((10^{-15} \text{ W m}^{-2})\) & \((10^{-15} \text{ W m}^{-2})\) & \\
\hline
BD +30 3639 & 2.50 ± 0.05 & 5.1 ± 0.3 & 5.64 ± 0.04 & 41.53 ± 0.04 & 6.26 ± 0.31 \\
IC 5117 & 0.25 ± 0.09 & 0.56 ± 0.2 & 0.75 ± 0.01 & 4.76 ± 0.01 & 1.17 ± 0.21 \\
PNG 093.9-00.1 & ... & ... & ... & 0.32 ± 0.05 & ...
\hline
\end{tabular}
\caption{Atomic Line Emission}
\end{table}

\begin{table}[h]
\centering
\begin{tabular}{|l|l|l|l|l|l|}
\hline
Object Name & 3.3 μm Peak & 3.3 μm FWHM & 3.3 μm EW & Aliphatic EW & Ratio 3.4/PAH & 3.3 μm Flux \\
& (μm) & (μm) & (μm) & (μm) & & \((10^{-15} \text{ W m}^{-2})\) \\
\hline
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 \\
\hline
\end{tabular}
\caption{PAH and Aliphatic Results}
\end{table}

\textbf{Note.} IC 5117 also showed emission in [Mg IV], with a flux of 4.1 ± 0.18(10^{-15} \text{ W m}^{-2}). Flux has been corrected for slit loss assuming the angular size in Table 2 and a 2" FLITECAM slit. Extraction width (arcsec): BD: 8.2 (3–3.35 μm), 8.4 (3.35–4.1 μm), 20.1 (4.2–5.41 μm); IC: 4.3 (3–3.35 μm), 3.7 (3.35–4.1 μm), 10.0 (4.2–5.41 μm); PNG: 6.1 (3–3.35 μm), 5.8 (3.35–4.1 μm), 5.4 (4.2–5.41 μm).

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

\textsuperscript{10} http://purl.com/net/mpfit
Gaussians at 3.4, 3.46, 3.51, and 3.56 μm, as identified by Jourdain de Muizon et al. (1990). The 3.3 μm feature was fit with a Gaussian simultaneously with the 3.4 μm feature. The 3.3 and 3.4 μm results are presented in Table 4 and discussed below. The 5.25 μm feature was also fit with a Gaussian using MPFIT, with results in Table 5.

### 4.2. 3.3 μm Aromatic Feature

Peeters et al. (2004) used the FWHM, peak wavelength and overall shape of the 6.2, 7.7, and 8.6 μm PAH spectra to classify the emission into three groups. This approach (though not the definitions of the classification groups) was extended to the 3.3 μm and 11.2 μm bands by several groups (e.g., van Dijckhoff et al. 2004). The 3.3 μm classification scheme uses band symmetry, FWHM, and central wavelength to categorize emission into three main classes, identified as Classes A3.3, B13.3, and B23.3 (van Dijckhoff et al. 2004). Class A3.3 exhibits symmetric emission centered at 3.290 μm with an FWHM of 0.040 μm, and is exhibited by most objects, including PNs. Class B13.3 and Class B23.3 exhibit asymmetric emission with an FWHM of 0.037 μm. Class B13.3 has a peak wavelength of 3.293 μm, while Class B23.3 peaks at 3.297 μm (van Dijckhoff et al. 2004). Tokunaga et al. (1991) used similar criteria to categorize 3.3 μm emission, with their class 1 equivalent to van Dijckhoff’s Class A3.3.

Previous studies have found little variation in the classification of 3.3 μm emission between different object classes, even though longer wavelength PAH emission can show much greater variation (Tokunaga et al. 1991; Peeters et al. 2002; van Dijckhoff et al. 2004; Cohen & Barlow 2005; Smith & McLean 2008). This may be because while the 6.2 and 7.7 μm features arise from stretching in the C–C bonds in the PAH molecules, the 3.3 and 11.2 μm features are due to stretching and out-of-plane bending modes of the C=H bonds (see Table 1 of Allamandola et al. 1989b), which may lead to smaller variation in emission in the 3.3 and 11.2 μm features.

The central wavelength and FWHM of the 3.3 μm feature were calculated by modeling the continuum at 3.0 and 3.8 μm, and then removing the contribution of the Pfund δ hydrogen emission line at 3.296 μm (see Section 4.1). Following the original classification papers (Peeters et al. 2002; van Dijckhoff et al. 2004; Tokunaga et al. 1991) we fit a symmetric Gaussian to the 3.3 μm emission feature using MPFIT (Markwardt 2009). It should be noted that the 3.3 μm emission is not a Gaussian, and was only approximated with a Gaussian for consistency with past classification schemes (e.g., Peeters et al. 2002). After calculating the central wavelength and FWHM, we applied the classifications used by van Dijckhoff et al. (2004) to the 3.3 μm emission of all three PN (see Table 4). As expected, the three PNs exhibit class A3.3 behavior, as is consistent with previous surveys (Tokunaga et al. 1991; Roche et al. 1996b; van Dijckhoff et al. 2004).

SOFIA does not have a field de-rotator, and FLITECAM has a single fixed slit for grism observations, so this survey did not sample multiple positions across the nebulae. Therefore, this technique would not detect subtle, spatially dependent variations in 3.3 μm emission within the nebulae. FLITECAM’s two second slit used for these observations does not sample the entirety of PNG 093.9-00.1 and BD +30 3639 or IC 5117. When slit losses are taken into account, the ground-based 3.3 μm fluxes reported in Cohen et al. (1989) are ~70% of our 3.3 μm fluxes for BD +30 3639 and IC 5117 (see Table 4).

### 4.3. Aliphatic Features

The 3.4 μm aliphatic emission complex has been observed as a band of emission sitting on top of the 3.2–3.6 μm plateau in most objects exhibiting 3.3 μm PAH emission, including H II regions (e.g., Sloan et al. 1997), proto-PNs (e.g., Hrivnak et al. 2007), external galaxies (e.g., Imanishi & Dudley 2000), and PNs (e.g., Geballe et al. 1985). The aliphatic emission feature is in general weaker than the PAH feature except in carbon-rich proto-PNs (Geballe & van der Veen 1990), where the 3.4 μm plateau can dominate the 3 μm spectrum. Kwok et al. (2001) have proposed that the apparent evolution from aliphatic-dominated to aromatic-dominated emission results from the destruction of aliphatics by the increasing UV field as objects evolve from UV weak proto-PNs to UV-hard PNs. The aliphatic band is sometimes observed as a series of individual peaks, rather than as a smooth feature above the 3.2–3.6 μm plateau. Jourdain de Muizon et al. (1990) identified these bands as occurring at 3.4, 3.46, 3.51, and 3.56 μm.

All three objects in this data set do exhibit emission above the 3.2–3.6 μm plateau in the 3.4–3.6 μm region (see Figures 1, 2, and 3). PNG 093.9-00.1 exhibited the most intense aliphatic emission in comparison with its PAH emission. Additionally, in the 3.4–3.6 μm region, PNG 093.9-00.1 shows evidence of the series of peaks occurring at 3.4, 3.46, 3.51, and 3.56 μm identified by Jourdain de Muizon et al. (1990). Aliphatic emission in IC 5117 and BD +30 3639 is much weaker in comparison to their PAH emission, and does not appear to exhibit the structure visible in PNG 093.9-00.1, instead appearing as a sharp rise at 3.4 μm, which trails off to continuum levels at ~3.6 μm. The lack of structure may be due to low S/N, rather than the emission itself. The equivalent width of this overall feature was calculated (see Table 4) and compared to the equivalent width of the aromatic 3.3 μm emission for each object. PNG 093.9-00.1 shows a higher aliphatic-to aromatic ratio than the other objects. Such a result is not unexpected as PNG 093.9-00.1 is a young object, exhibits multipolar morphology (with a binary central object), and is known to have stronger than expected 3.4 μm emission.

### Table 5

| Object Name | Extraction Width(arcsec) | 5.25 μm Peak (μm) | 5.25 μm FWHM (μm) | 5.25 μm EW (μm) | 5.25 μm Flux (10^{-18} W m^{-2}) |
|-------------|--------------------------|------------------|------------------|----------------|----------------------------------|
| 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 2 and a 2″ FLITECAM slit.
emission wavelength slightly blueshifted from the more evolved PNs. Additionally, the shape of the PAH emission in PNG 093.9-00.1 is more asymmetric. The underlying structure of the aliphatic emission is also more apparent in PNG 093.9-00.1, with peaks at 3.4, 3.46, 3.51, and 3.56 μm. Even the ratio of the PAH to aliphatic emission is different in this object, with the aliphatic emission in PNG 093.9-00.1 stronger in comparison to its 3.3 μm emission than the other objects. These differences 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. A study of the spatial variations within these PNs would potentially uncover additional emission variations due to nebular conditions.

5. Conclusions

Using the grism spectroscopy mode of FLITECAM on board SOFIA, we obtained 3–5.41 μm spectra of three PNs IC 5117 and BD +30 3639 and PNG 093.9-00.1. Because SOFIA flies above 99% of Earth’s water vapor, this allowed investigation of not just the bright 3.3 μm PAH emission, but also the fainter 3.4–3.6 μm aliphatic emission feature as well as the faint 5.25 μm feature. From these data the 3–5.41 μm spectrum of PNG 093.9-00.1 does show some minor variations from IC 5117 and BD +30 3639, appearing to exhibit relatively more aliphatic chemistry than the other PNs.

(1) All three objects showed PAH emission, with FWHM and central wavelength consistent with that found by Tokunaga et al. (1991), and corresponding to Class A\textsubscript{3.3} emission.

(2) Aliphatic emission was observed in the 3.4–3.6 μm range of all three targets, with PNG 093.9-00.1 showing strong aliphatic emission in comparison to its aromatic (3.3 μm) emission. The observed differences may be due to morphology, central star temperature, or age, but also could be due to spatial variations within the objects. An investigation into the spatial variation of PAH and aliphatic emission in PNs could reveal important clues about PAH formation and evolution.

(3) No emission from deuterated PAHs was detected.

(4) The 5.25 μm feature was detected in all three objects.

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Facility: SOFIA (FLITECAM).

Software: IDL, ATRAN code (Lord 1992), MPFIT (Markwardt 2009), REDUX (Clarke et al. 2015), Spextool (Cushing et al. 2004), XGAUSSFIT (Lindler 2001).

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