Publications of the Korean Astronomical Society
32: 087 ∼ 091, 2017 March

pISSN 1225-1534
eISSN 2287-6936
https://doi.org/10.5303/PKAS.2017.32.1.087

NEAR-INFRARED PAH FEATURES IN GALACTIC PLANETARY NEBULAE

R. Ohsawa[1], O. Onaka[2], I. Sakon[2], T. I. Mori[2], H. Kaneda[3], and M. Matsuura[4]
[1]Institute of Astronomy, Graduate School of Science, The University of Tokyo, 118-0015, 2-21-1 Osawa, Mitaka, Tokyo, Japan
[2]Department of Astronomy, Graduate School of Science, The University of Tokyo
[3]Division of Particle and Astrophysical Sciences, G, Nagoya University
[4]Department of Physics & Astronomy, University College London
E-mail: ohsawa@astron.s.u-tokyo.ac.jp

(Received September 30, 2014; Revised October 21, 2016; Accepted October 21, 2016)

ABSTRACT

Polycyclic aromatic hydrocarbons (PAHs) are considered to be carriers of the unidentified infrared bands, which are ubiquitously observed in the Universe. PAHs are mainly formed around evolved carbon-rich stars and injected into interstellar space. Planetary nebulae (PNe), a late stage of low- and intermediate stellar mass evolution, are suitable objects to investigate the formation and evolution of PAHs. The shortest PAH feature is located in 3.3 μm, which is important to examine the excitation and size distribution of PAHs. While the number of samples had been limited before, the high sensitivity of *AKARI*/IRC has drastically increased the number of samples. We obtained the 2–5 μm spectra of Galactic PNe with *AKARI*/IRC and compiled a near-infrared spectral catalog, containing 73 PNe. We investigate the detection rate and the evolution of the PAH features. The characteristics of the catalog are illustrated and the origin of the evolution of the PAH features is discussed.

Key words: planetary nebulae: general — dust, extinction

1. INTRODUCTION

Polycyclic aromatic hydrocarbons (PAHs) are carbonaceous small dust grains made of fused aromatic rings with peripheral hydrogen atoms (Allamandola et al., 1989; Tielens, 2008). They are typically ∼5–30 Å in diameter, containing ∼30–1000 carbon atoms. They are thought to be carriers of the unidentified infrared (UIR) bands, which are widely detected in various astronomical objects in the Universe (Peeters et al., 2002b; Acke & van den Ancker, 2004). It is suggested that PAHs are related to the carriers of the 2175 Å bump or the diffuse infrared bands (Sarre, 2006; Joblin et al., 1992). The origin and evolution of PAHs are important topics to understand interstellar materials.

PAHs are though to be formed around carbon-rich AGB and post-AGB stars and then injected into interstellar space. Planetary nebulae (PNe), evolved from post-AGB stars, frequently show the PAH features and possess PAHs in their circumstellar envelope. They are suitable objects to investigate the evolution of the PAH features from circumstellar to interstellar environments.

PAHs absorb a single UV-photon, excite their vibrational modes, and produce distinct emission features in the infrared. Thus, the PAH features are mainly emitted in photo-dissociation regions. Although the spectral shape of the PAH features look similar among objects, there are some variations in the width, the central wavelength and the relative intensities (Peeters et al., 2002a; Matsuura et al., 2014). These variations are thought to indicate the physical conditions and chemical structure of PAHs (e.g., Hony et al., 2001; DeFrees et al., 1993).

The PAH feature at 3.3 μm, attributed to aromatic C-H stretching modes, is the shortest in wavelength and efficiently emitted from small-sized PAHs (Schutte et al., 1993). In the 3.4–3.5 μm wavelengths, there are the PAH features attributed to aliphatic C-H stretching modes. The PAH features in the 3 μm region are indispensable to investigate the excitation, size distribution and chemical structure of PAHs (Mori et al., 2012, 2014).

The 2–5 μm region is available with ground-based telescopes, but the signal-to-noise ratio is degraded by severe atmospheric absorption and increasing thermal background at $\gtrsim$3 μm. Observations with space telescopes are preferable. The *ISO*/SWS has a capability of obtaining 2–40 μm continuous spectra with the spectral resolution of $R \sim 600$. More than 80 PNe are observed by the *ISO*/SWS and their spectra are available in the *ISO*/SWS archive. Due to the limited sensitivity in the near-infrared, however, the number of samples with a sufficient signal-to-noise ratio in the 2–5 μm is limited. Observations of the near-infrared spectra of PNe with a high sensitivity are required for detailed investigation of the 3 μm PAH features.

The infrared camera (IRC) onboard *AKARI*, which is able to obtain 2–5 μm spectrum with the sensitivity of $\sim$ 10 mJy, is a suitable instrument to investigate the 3 μm PAH features (Onaka et al., 2007). In the post-helium phase, the spectra of 73 Galactic PNe were obtained with the IRC. We measure the intensities of the 3.3 μm and 3.4–3.5 μm PAH features. The intensities, as well as the spectra themselves, are going to be published as a catalog (hereafter, PNSPC catalog), which is the largest and most suitable samples to investigate the 3 μm PAH features of PNe.

In this paper, we discuss the evolution of the 3 μm PAH features during the PN phase based on the PNSPC catalog. The paper is organized as follows. The characteristics of the PNSPC catalog are described in Section 2. The variations in the 3 μm PAH features are presented in Section 3 and their origin is discussed in Section 4. The paper is summarized in Section 5.

2. NIR SPECTRAL CATALOG OF GALACTIC PNe

In the AKARI Phase 3 program, PNSPC, the 2.5–5.0 μm spectra of 73 Galactic PNe were obtained with the IRC. The spectrum contains the 3.3 μm and 3.4–3.5 μm PAH features. The intensities of these features were measured by fitting with a combination of Lorentzian functions. Thanks to the high sensitivity of the IRC, the detection limit of the 3.3 μm PAH feature was about 10^{-16} W m^{-2}.

The observations were carried out with the grism spectroscopy mode in the $1' \times 1'$ window, which enabled us to collect photons without loss due to the slit efficiency. In Figure 1, we examine the accuracy of the absolute flux of the PNSPC catalog by comparing the *WISE* All-Sky Release catalog (Cutri et al., 2012). The vertical axis shows the *WISE* $W1$ flux estimated from the PNSPC spectra ($F_{W1,\mathrm{IRC}}$), while the horizontal axis shows the *WISE* $W1$ flux from the All-Sky catalog ($F_{W1,\mathrm{WISE}}$). The gray thick line indicates $F_{W1,\mathrm{IRC}} = F_{W1,\mathrm{WISE}}$. The PNSPC spectra are consistent with the WISE from about 10 mJy to 1 Jy. Figure 1 shows that the intensities of the PAH features we have measured are reliable.

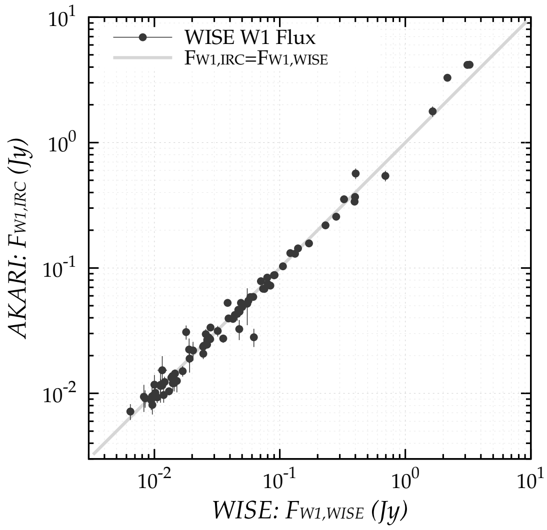

Figure 1. Comparison with the WISE All Sky catalog. The $W1$ flux estimated from the PNSPC spectra ($F_{W1,\mathrm{IRC}}$) is shown against the $W1$ flux from the WISE All-Sky catalog ($F_{W1,\mathrm{WISE}}$). The loci of $F_{W1,\mathrm{IRC}} = F_{W1,\mathrm{WISE}}$ are indicated by the gray thick line.

Figure 2 shows the cumulative histogram of the signal-to-noise ratio of the 3.3 μm PAH feature, indicating that the 3.3 μm PAH feature is detected in about 65% of the PNe when we adopt a 3-σ detection limit. Based on the *Spitzer*/IRS spectra of Galactic PNe, however, Stanghellini et al. (2012) report that the frequency of the PNe with carbon-rich dust features is about 0.53. Thus, the PAH detection rate in the mid-infrared is not more than $\sim$0.53. The PAH detection rate is higher in the near-infrared than in the mid-infrared, although the 3.3 μm PAH feature is typically weaker than those in the mid-infrared. This is possibly because that the 3.3 μm feature is not suffered from the contamination by other dust features such as HACs. This result indicates that the PNSPC catalog is suitable to investigate a small variation in the intensity of the PAH features.

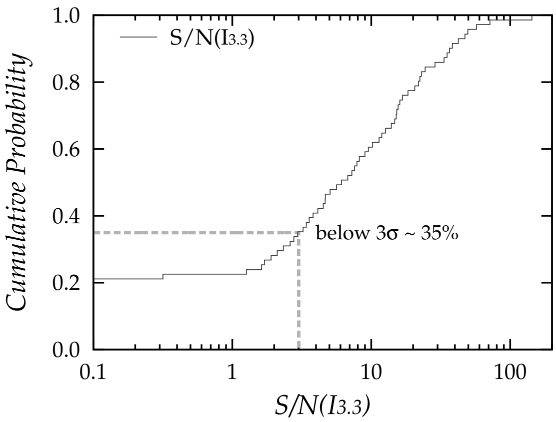

Figure 2. Cumulative histogram of the signal-to-noise ratio of the 3.3 μm PAH feature.

3. EVOLUTION OF THE 3 μm PAH FEATURES

The effective temperature ($T_{\rm eff}$) of PNe increases as a PNe evolves. We use $T_{\rm eff}$ as an indicator of the PN evolution as used for post-AGB stars (Sloan et al., 2007; Matsuura et al., 2014). The effective temperatures are obtained from literature (Phillips, 2003; Lumsden et al., 2001; Preite-Martinez et al., 1989, 1991).

The upper panel of Figure 3 shows the variation in the intensity ratio of the 3.3 μm PAH feature to the total infrared emission ($I_{3.3}/I_{\rm IR}$) against $T_{\rm eff}$. The total infrared intensity ($I_{\rm IR}$) is estimated from the broad-band photometric data of the *AKARI*/IRC Point Source Catalogue, *AKARI*/FIS Bright Source Catalogue, and *WISE* All-Sky Release Catalog (Ishihara et al., 2010; Yamamura et al., 2010; Cutri et al., 2012). The $I_{3.3}/I_{\rm IR}$ indicates the relative amount of PAHs which is excited by UV photons. The variation in the median value is shown by the thick solid line with the circles. The error bars shows a typical variation in the median value, estimated from a Monte Carlo simulation. In the earlier phase ($T_{\rm eff} \lesssim 50,000$ K), the $I_{3.3}/I_{\rm IR}$ ratio decreases with increasing $T_{\rm eff}$. After that, the ratio increases with $T_{\rm eff}$.

The lower panel of Figure 3 shows the intensity ratio of the 3.4–3.5 to 3.3 μm PAH features ($I_{3.4}/I_{3.3}$), which indicates the relative amount of aliphatic components in PAHs. The variation in the median value is shown by the thick solid line as in the upper panel. The $I_{3.4}/I_{3.3}$ rapidly increases as $T_{\rm eff}$ increases to 40,000 K, and then the ratio keeps a high value. The result indicates that the relative amount of the aliphatic components in PAHs increases with PN evolution.

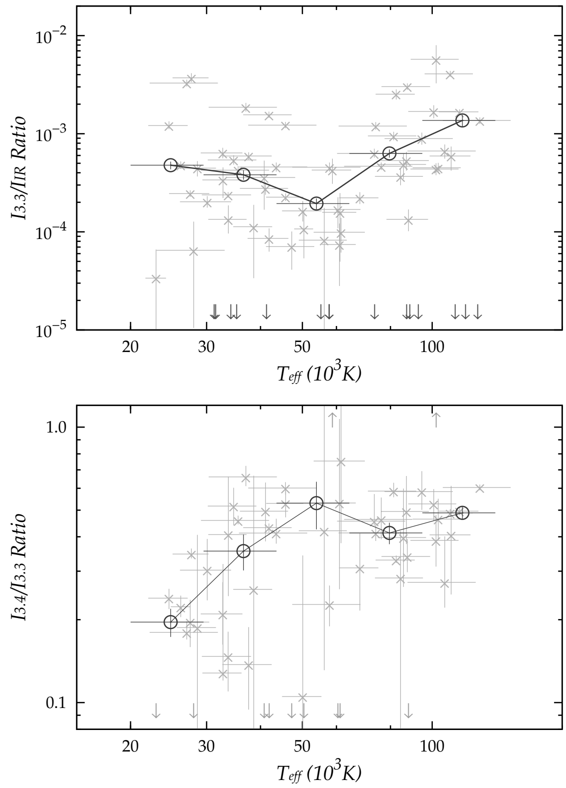

Figure 3. (Upper) Evolution of the relative amount of PAHs. The gray crosses with error bars show the individual $I_{3.3}/I_{\rm IR}$ ratios. The thick solid line with the circles indicates the variation in the median value. (Lower) Evolution of the aliphatic-to-aromatic ratio of PAHs. The $I_{3.4}/I_{3.3}$ ratio is shown by the gray crosses with error bars. The thick solid line is the same as in the upper panel.

4. DISCUSSION

The decrease in the $I_{3.3}/I_{\rm IR}$ ratio in the early phase may be attributed to the destruction of PAHs. PAHs can be photo-dissociated when they are radiated by intense UV radiations (Allain et al., 1996a,b). The central star of PNe is sufficiently hot to produce high-energy UV photons to destroy PAHs. PAH destruction may proceed as $T_{\rm eff}$ increases. When PAHs are exposed to a hot ionized gas, PAHs can be destroyed by ion-sputtering (Micelotta et al., 2010). The central star is surrounded by a hot H II region heated by a reverse shock. The H II region may expand with increasing $T_{\rm eff}$, destroying PAHs in the envelope. The number of ionizing photons, however, does not increase with $T_{\rm eff}$ when $T_{\rm eff} \gtrsim 70,000$ K since the central star evolves with a constant luminosity. This may explain that the $I_{3.3}/I_{\rm IR}$ ratio stops to decrease after $T_{\rm eff} \gtrsim 50,000$ K.

The $I_{3.3}/I_{\rm IR}$ ratio increases with $T_{\rm eff}$ when $T_{\rm eff} \gtrsim 50,000$ K. It is not possible to form extra PAHs from a circumstellar gas since PNe are too diffuse to form dust from a gas. UV photo-processing of small carbonaceous dust grains may produce extra PAHs by increasing aromatic components in carbonaceous dust. But this process decreases the $I_{3.4}/I_{3.3}$ ratio (Goto et al., 2000). PAH formation by photo-processing is not consistent with the present results. No PAH formation process can explain the increase in the $I_{3.3}/I_{\rm IR}$ ratio.

We propose that the increase in the $I_{3.3}/I_{\rm IR}$ ratio is attributed to the expansion of the photo-dissociation region. The circumstellar envelope of a PN is typically optically thick in the UV, especially for a young PN (Ohsawa et al., 2012). UV photons cannot penetrate deeply into the circumstellar envelope. Thus, the PAHs located in the outer part of the envelope are not excited when the PN is young. As the envelope expands, the optical depth at UV decreases. Then, UV photons become able to penetrate deeper into the envelope and excite more PAHs. The variation in the $I_{3.4}/I_{3.3}$ ratio is explained by assuming that the PAHs near the central star have a smaller amount of aliphatic components. When a PN is young, only the PAHs near the central star are excited, resulting in a small $I_{3.4}/I_{3.3}$ ratio. As the PN evolves, the PAHs near the central star are destroyed and the PAHs located in the outer part, with a larger $I_{3.4}/I_{3.3}$ ratio, are excited. The expansion of the envelope and photo-dissociation region can consistently explain the present results.

In the proposed scenario, we assume that the aliphatic components are scarce in the PAHs near the central star. This suggests that the PAHs formed in the post-AGB phase have a smaller amount of aliphatic components than those formed in the AGB phase. Physical environments such as UV radiation fields in PAH formation may affect the aliphatic-to-aromatic ratio of PAHs. Alternatively, the PAHs near the central star had lost their aliphatic components by UV photo-processing during the post-AGB phase. Further investigation is required to identify the reason that young PNe typically show a small $I_{3.4}/I_{3.3}$ ratio.

5. SUMMARY

We investigate the evolution of the near-infrared PAH features in Galactic PNe based on the near-infrared spectra obtained with the *AKARI*/IRC. Thanks to the high sensitivity achieved by the IRC, we successfully build a spectroscopic catalog which is suitable to investigate the variations in the $3\,\mu$m PAH features.

We use the effective temperature of the central star as an indicator of the evolutionary phase of the PN. The relative amount of PAHs decreases with PN evolution at first, and then increases when $T_{\rm eff} \gtrsim 50,000\,$K. The relative amount of aliphatic components in PAHs increases in an early stage of PN evolution. We propose that these variations are attributed to the destruction of PAHs and the expansion of the photo-dissociation region. When the PN is young, only the PAHs near the central star are excited since the circumstellar envelope is optically thick in the UV and PAHs efficiently destroyed by UV radiation or ion-sputtering. As the PN evolves, the optical depth of the envelope decreases. More PAHs, which is located far from the central star, are excited, increasing the $I_{3.3}/I_{\rm IR}$ ratio. The PAHs near the central star is expected to be formed in the post-AGB phase. If the PAHs formed in the post-AGB phase have a small amount of aliphatic components or the PAHs near the central star had lost their aliphatic components due to the processing in the post-AGB phase, the expansion of the photo-dissociation region consistently explain the increase in the $I_{3.4}/I_{3.3}$ ratio. Further investigation is required to confirm the proposed scenario, but it is notable that not all the PAHs in the envelope are excited even in the PN phase and that the time variation in the PAH features is not necessarily attributed to the evolution of PAHs.

ACKNOWLEDGMENTS

This research is supported in part by Grants-in-Aid for Scientific Research (25-8492, 25-2763) by the Japan Society of Promotion of Science. This research is based on observations with *AKARI*, a JAXA project with the participation of ESA. We are grateful to all the people who work in the AKARI project.

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