

# **Evolution of polycyclic aromatic hydrocarbons (PAHs) in the interstellar medium revealed by AKARI**

(あかりで探る星間空間における PAH の進化)

森 珠実

We present the results of observational studies of the processing of polycyclic aromatic hydrocarbons (PAHs) in the interstellar medium (ISM) based on infrared (IR) slit spectroscopy of the Infrared Camera (IRC) on board *AKARI* and laboratory work on deuterated hydrocarbon materials motivated by these studies. The IR wavelength region contains many emission and/or absorption features associated with various kinds of gaseous and solid materials in the ISM. The diffuse IR light coming from the ISM tells us much about interstellar matters and thus much about the interstellar environment and the evolution of materials in the universe. Among these IR features, we focus on a series of prominent emission bands, called the unidentified infrared (UIR) bands, whose carrier is generally thought to be PAHs and/or their relative compounds (see Figure 1 for the typical spectrum). *AKARI*'s unique advantages are the unprecedented sensitivity in the 2–5  $\mu\text{m}$  near-infrared (NIR) wavelength range, especially for diffuse sources, and the simultaneous coverage of 2–13  $\mu\text{m}$  in the same slit area. We take advantage of these characteristics while demonstrating that NIR spectroscopy is important for exploring the evolution of PAHs in the ISM.

In the 2–5  $\mu\text{m}$  spectrum of astronomical objects, a prominent emission band appears at 3.3  $\mu\text{m}$ . The relative intensity of the 3.3  $\mu\text{m}$  band to the UIR bands at longer wavelengths, especially the 11.3  $\mu\text{m}$  band, is considered to be the most robust PAH size distribution indicator. Although size distribution is one of the most important factors

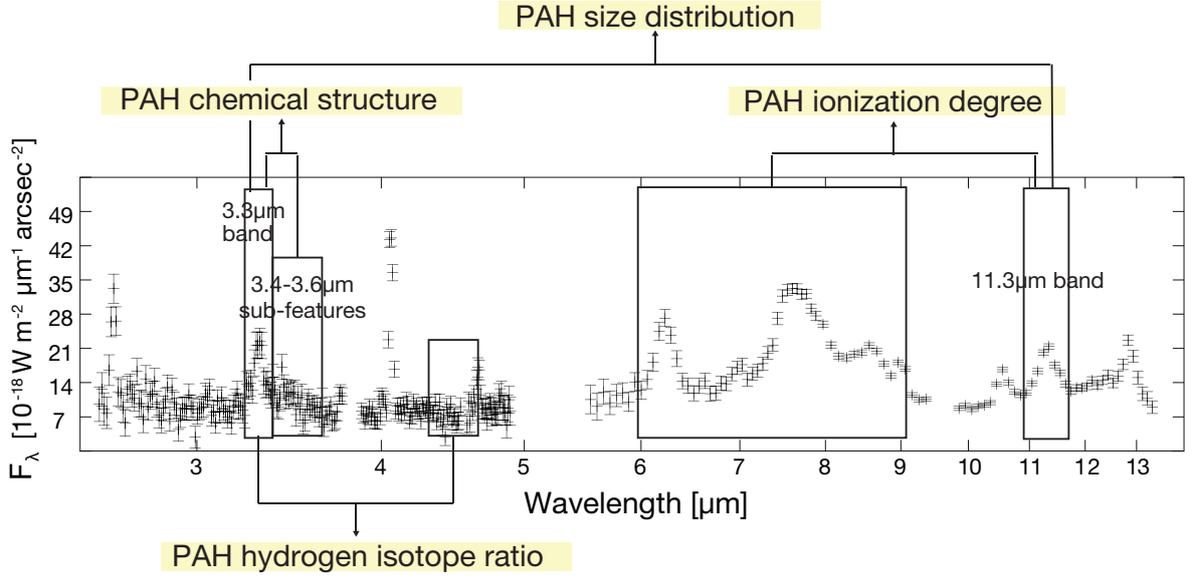


Figure 1: The typical 2–13  $\mu\text{m}$  spectrum of the ISM obtained by the *AKARI/IRC*.

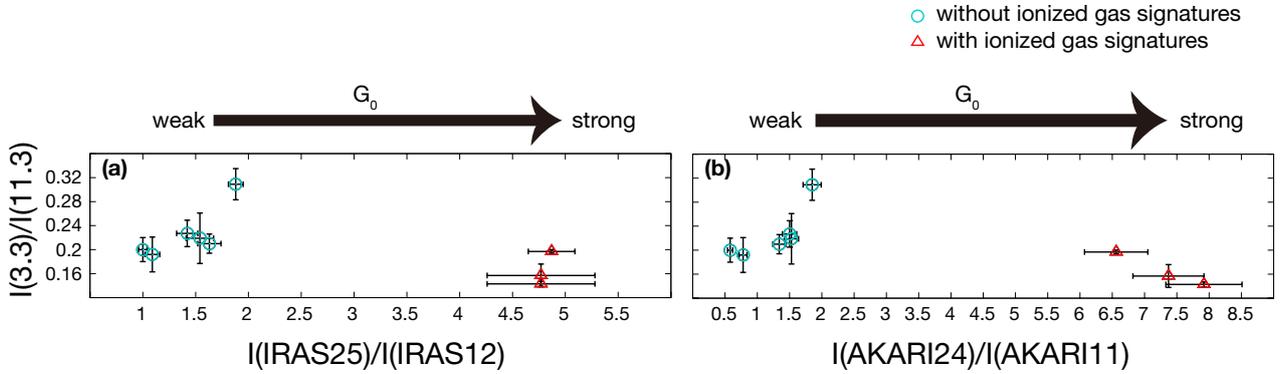


Figure 2: Variation of the UIR band ratios of the 3.3  $\mu\text{m}$  to the 11.3  $\mu\text{m}$  band against (a) the *IRAS* color of  $I_{25\mu\text{m}}/I_{12\mu\text{m}}$  and (b) the *AKARI* color of  $I_{L24}/I_{S11}$ . The turquoise open circles and the red open triangles with the black error bars indicate the UIR band ratios and the *AKARI* or *IRAS* colors, respectively, of those without ionized gas signature and the other H II region-like targets. The UIR band ratios are corrected for the extinction and the contribution from the hydrogen recombination lines.

of PAH processing, the ratio of the 3.3 to 11.3  $\mu\text{m}$  band,  $I_{3.3\mu\text{m}}/I_{11.3\mu\text{m}}$ , has not yet been carefully investigated, due to the difficulty of simultaneous observations at these largely separated wavelengths. Here, from simultaneous slit spectroscopy at 2–5  $\mu\text{m}$  NIR and 5–13  $\mu\text{m}$  MIR wavelengths of the diffuse light of the Large Magellanic Cloud (LMC) by the *AKARI/IRC*, we systematically investigated the intensity ratios of the UIR bands appearing from 2 to 13  $\mu\text{m}$  for the first time. The observations were performed toward nine positions of the LMC. In order to cover a wide range of radiation conditions, the target positions are chosen such that each has different *IRAS* 25 to 12  $\mu\text{m}$  and 60 to 100  $\mu\text{m}$  color, which are sensitive to massive star-forming activities. Among the regions without ionized gas signatures, the ratio of the 3.3 to 11.3  $\mu\text{m}$  band shows a positive correlation with the *IRAS* 25 to 12  $\mu\text{m}$  and *AKARI* 24 to 11  $\mu\text{m}$  band colors, whereas the other H II region-like targets do not follow this sequence (see Figure 2). In the latter targets, the ratio of the 3.3 to 11.3  $\mu\text{m}$  band is much smaller than extrapolation from the correlation. This difference is successfully accounted for in terms of the paucity of very small PAHs ( $n_C < 100$ ) in H II region-like targets, which is possibly due to preferential destruction of very small PAHs in ionized gas-dominated regions. This result clearly demonstrates that the diagram of the ratio of the 3.3 to 11.3  $\mu\text{m}$  band v.s. the ratio of the 7.7 to 11.3  $\mu\text{m}$  band can be a good probe for local star-forming activity.

The intensity ratio of the 3.4–3.6  $\mu\text{m}$  bands to the 3.3  $\mu\text{m}$  band can also indicate PAH alteration. The sub-features that commonly appear at approximately 3.4–3.6  $\mu\text{m}$ , next to the PAH 3.3  $\mu\text{m}$  band, are associated with the vibration modes of aliphatic C-H bonds such as branched alkyl groups and chain structures. On the other hand, the 3.3  $\mu\text{m}$  band is assigned to aromatic C-H bonds. The intensity ratio of the 3.4–3.6  $\mu\text{m}$  bands to the 3.3  $\mu\text{m}$  band can therefore be used as a tracer of the structure of interstellar PAHs. Using a large collection of high-quality NIR spectra (2.5–5.4  $\mu\text{m}$ ) of galactic H II regions and H II region-like objects, we investigated the UIR bands at NIR wavelengths. Thirty-six objects were observed by the *AKARI*/IRC as a part of a director’s time program. The analysis shows that the aliphatic to aromatic ratio of  $I_{3.4-3.6 \mu\text{m}}/I_{3.3 \mu\text{m}}$  decreases against the ratio of the 3.7  $\mu\text{m}$  continuum intensity to the 3.3  $\mu\text{m}$  band,  $I_{\text{cont},3.7 \mu\text{m}}/I_{3.3 \mu\text{m}}$ , which is an indicator of the ionization fraction of PAHs (see Figure 3). The *AKARI* MIR color of  $I_{9 \mu\text{m}}/I_{18 \mu\text{m}}$  also decreases steeply against the ratio of the hydrogen recombination line Br $\alpha$  at 4.05  $\mu\text{m}$  to the 3.3  $\mu\text{m}$  band,  $I_{\text{Br}\alpha}/I_{3.3 \mu\text{m}}$ . These facts indicate possible dust processing inside or at the boundary of ionized gas. In addition to the 3.3–3.6  $\mu\text{m}$  band complex, most spectra show a relatively weak emission feature at 5.22  $\mu\text{m}$  with sufficient signal-to-noise ratios, which we identify as the PAH 5.25  $\mu\text{m}$  band previously reported. By careful analysis, we found good correlation between the 5.25  $\mu\text{m}$  band and both the aromatic hydrocarbon feature at 3.3  $\mu\text{m}$  and the aliphatic ones at approximately 3.4–3.6  $\mu\text{m}$ . The present results provide us convincing evidence that the astronomical 5.25  $\mu\text{m}$  band is associated with C-H vibrations of PAHs, as suggested by previous studies, showing its potential to probe the PAH size distribution.

It is also known that deuterated PAHs (PADs) exhibit emission features at approximately 4.3–4.8  $\mu\text{m}$  instead of 3.3–3.5  $\mu\text{m}$  because of the difference in the reduced mass between the C–H and C–D oscillators. PAHs are thought to be a possible reservoir of missing deuterium (D) in the ISM. However, the latest results of *AKARI* NIR slit spectroscopy suggest that there is no significant signature at 4.3–4.8  $\mu\text{m}$  showing the incorporation of deuterium into PAHs. There still remains a mystery about the refuge of deuterium in the ISM. To investigate a possible effect on the cross-section by deuteration quantitatively, we generated deuterated hydrocarbon materials in the laboratory in a similar way to the synthesis of quenched carbonaceous composites (QCCs). We then measured their 2–25  $\mu\text{m}$  IR spectra and hydrogen isotope ratios, using a Fourier transform infrared spectrometer (FT-IR) and a nanoscale secondary ion mass spectrometer (NanoSIMS). By using a mixture of methane and perdeuterated methane gas with five different mixing ratios as the starting material, we investigated the spectral transitions from non-deuterated to perdeuterated hydrocarbon materials. Deuteration does not change the cross-section at NIR wavelengths significantly, which supports our interpretation of the *AKARI* results that PAHs are not the dominant carrier of deuterium in the ISM. Furthermore, we found a new feature peaking at 20.4  $\mu\text{m}$ , which is possibly due to combination of C-C-C out-of-plane and C-D out-of-plane vibration modes. We suggest that this feature can be a PAD tracer at MIR wavelengths.

As described above, we investigated the evolution of PAHs in the ISM in terms of size distribution, chemical structure, and hydrogen isotope ratio. These ISM properties are revealed in the NIR spectroscopic range, via *AKARI*

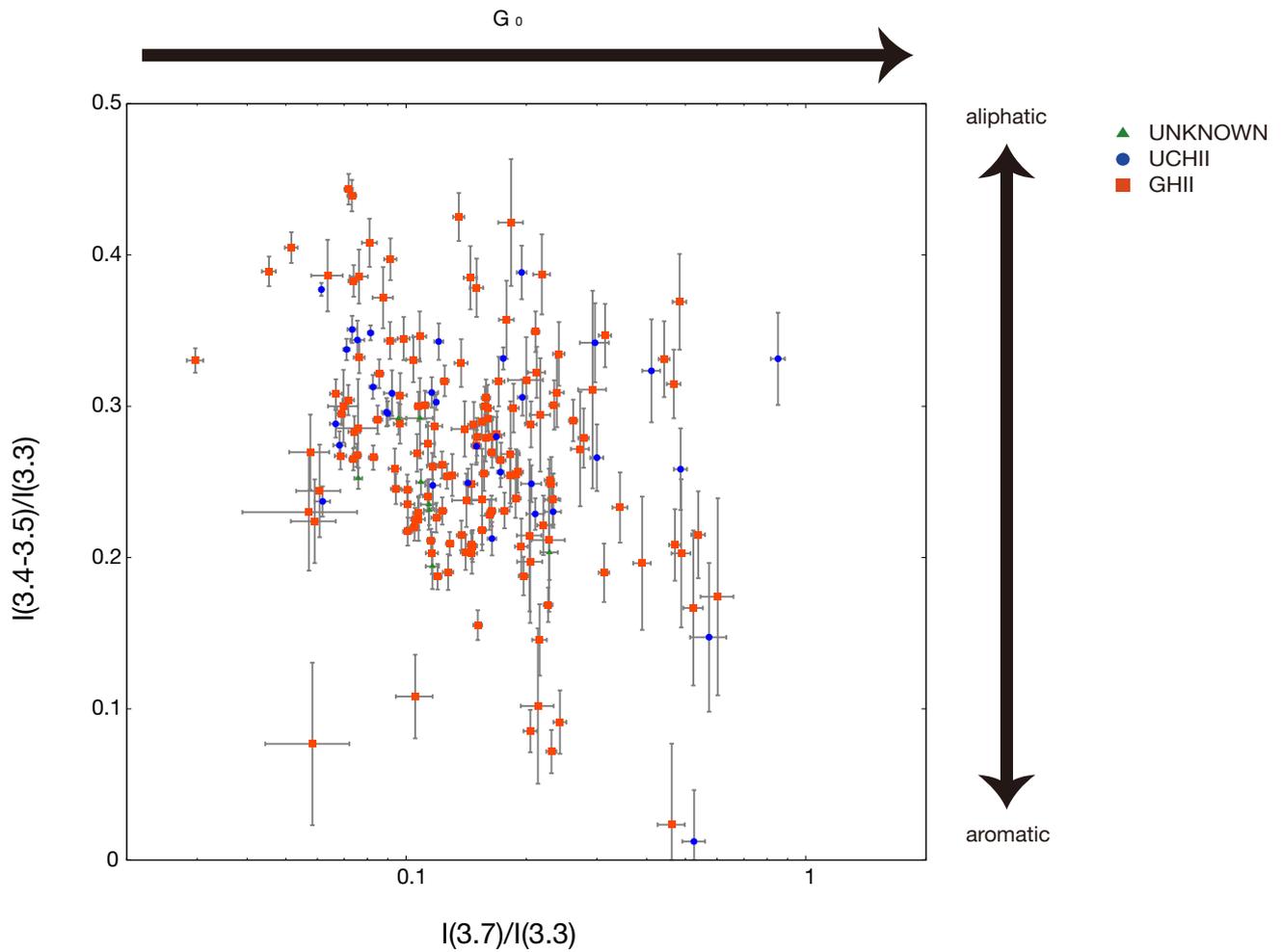


Figure 3: Diagram of the relative intensity ratio of the 3.4–3.6  $\mu\text{m}$  sub-features to the 3.3  $\mu\text{m}$  band,  $I_{3.4-3.6 \mu\text{m}}/I_{3.3 \mu\text{m}}$ , versus that of the 3.7  $\mu\text{m}$  continuum intensity to the 3.3  $\mu\text{m}$  band,  $I_{\text{cont}, 3.7 \mu\text{m}}/I_{3.3 \mu\text{m}}$ .

observations and subsequent laboratory experiments. In particular, the size distribution and chemical structure of PAHs vary according to the host environment, suggesting that PAHs can be a useful diagnostic tool for interstellar environments.