Publications of the Korean Astronomical Society
27: 209 ∼ 212, 2012 September

ISSN 1225-1534 (Print)
http://dx.doi.org/10.5303/PKAS.2012.27.4.209

NEAR- TO MID-INFRARED SLIT SPECTROSCOPIC OBSERVATIONS OF THE UNIDENTIFIED INFRARED BANDS IN THE LARGE MAGELLANIC CLOUD

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(Received June 28, 2012; Accepted August 04, 2012)

ABSTRACT

We present the results of the near-infrared (NIR) to mid-infrared (MIR) slit spectroscopic observations of the diffuse emission toward nine positions in the nearby irregular galaxy Large Magellanic Cloud (LMC) with the Infrared Camera (IRC) on board *AKARI*. The unique characteristic of *AKARI*/IRC provides a great opportunity to analyze variations in the unidentified infrared (UIR) bands based on continuous spectra from 2.5 to 13.4 μm of the same slit area. The observed variation of $I_{3.3}/I_{11.3}$ suggests destruction of small-sized UIR band carriers, polycyclic aromatic hydrocarbons (PAHs) in harsh environments. This result demonstrates that the UIR 3.3 μm band provides us powerful information on the excitation conditions and/or the size distribution of PAHs, which is of importance for understanding the evolutionary process of hydrocarbon grains in the Universe. It also suggests a new diagnostic diagram of two band ratios, such as $I_{3.3}/I_{11.3}$ versus $I_{7.7}/I_{11.3}$, for the interstellar radiation conditions. We discuss on the applicability of the diagnostic diagram to other astronomical objects, comparing the LMC results with those observed in other galaxies such as NGC 6946, NGC 1313, and M51.

Key words: dust, extinction; infrared: ISM; Magellanic Clouds; galaxies

1. INTRODUCTION

The unidentified infrared (UIR) bands refer to a series of near-infrared (NIR) to mid-infrared (MIR) prominent wide emission bands seen at 3.3, 6.2, 7.7, 8.6, 11.3, 12.7, and 16.4 μm together with some faint features. The carriers of the bands are thought to be polycyclic aromatic hydrocarbons (PAHs) or PAH-containing carbonaceous compounds (e.g., Allamandola et al., 1989). PAHs are the smallest members of the interstellar dust and are vulnerable to harsh conditions in the interstellar medium (ISM). They should manifest the effects of dust processing most clearly. Recent progress in PAH studies based on laboratory experiments and quantum chemical calculations suggests that the properties of the bands (e.g., inter-band intensity ratios) reflect the chemical and physical properties of PAHs, which are altered according to the physical conditions of the host environments (Tielens, 2008). In parallel with this progress, the existence of the band emission is reported in various astronomical objects, even in distant galaxies (e.g., Sajina et al., 2007). These previous works indicate that the UIR bands have a great potential of being an efficient tool to investigate the processing in ISM and probe physical conditions even in distant galaxies, which will give us a key to understand the life cycle of the interstellar matter and the cosmic chemical evolution.

Particularly, the UIR 3.3 μm band is dominated by

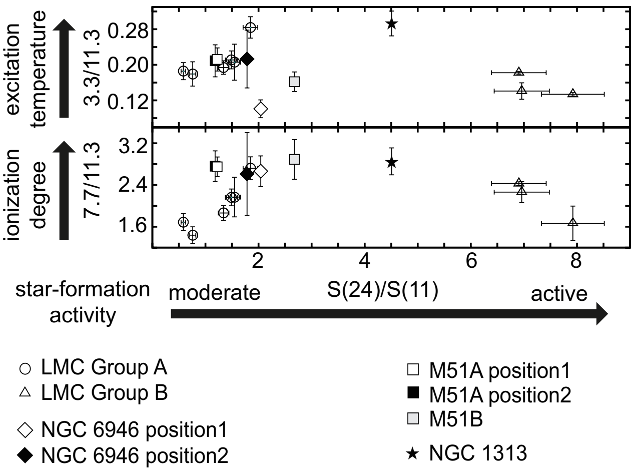

Fig. 1. Variation of the UIR band ratios of the 3.3 μm to the 11.3 μm band (a), and the 7.7 μm to the 11.3 μm against the *AKARI* color of S_{24}/S_{11}.

emissions originating from small-sized PAHs ($n_C \lesssim 100$) (Draine & Li, 2007), and thus the intensity ratio of $I_{3.3}/I_{11.3}$ is supposed to be very sensitive to the PAH size distribution and/or excitation conditions. However, detailed observational studies of $I_{3.3}/I_{11.3}$ have not been performed due to observational constraints, while the band ratios among the MIR bands, such as the ionized-to-neutral PAH band, $I_{7.7}/I_{11.3}$, are investigated dedicatedly in many astronomical objects by *Spitzer* and other facilities. This work is the first analysis of the UIR band ratios including $I_{3.3}/I_{11.3}$ extracted from exactly the same area. It shows that $I_{3.3}/I_{11.3}$ can trace the history of PAH destruction from the perspective of PAH size distribution, which is difficult to derive only from MIR observations.

2. OBSERVATIONS AND RESULTS

2.1. NIR and MIR Slit Spectroscopic Observations

We have performed NIR and MIR slit spectroscopic observations using the Infrared Camera (IRC) on board *AKARI* (Murakami et al., 2007, Onaka et al., 2007), toward nine positions in the Large Magellanic Cloud (LMC). The LMC is a nearby irregular galaxy and is located at the distance of 50 kpc from the Milky Way (Keller & Wood, 2006). In addition to its proximity, the almost face-on orientation ($i \sim 35°$; Nikolaev et al., 2004) allows us to investigate emissions from the ISMs with little confusion along the line of sight. The nine target positions are selected based on *IRAS* colors of S_{25}/S_{12} and S_{60}/S_{100} (Sakon et al., 2006) and CO mapping data (Mizuno et al., 2001), to cover a wide range of radiation field conditions.

Since the beam splitter of the IRC enables us to perform simultaneous spectroscopic observations for the NIR and MIR for the same slit area ($5'' \times 1'$), we can accurately investigate the intensity ratios among the UIR bands from 2.5 to 13.4 μm at each target position. The extinction and the contribution from the hydrogen recombination lines are corrected for in the estimation of the band intensities (see Mori et al., 2012, for details).

2.2. Observational Results

Among six positions whose spectra do not show apparent ionization signatures (classified into Group A), the ratio of $I_{3.3}/I_{11.3}$, which is sensitive to the excitation temperature of PAHs, and the ratios of $I_{6.2}/I_{11.3}$, $I_{7.7}/I_{11.3}$ and $I_{8.6}/I_{11.3}$, which can be used to infer the ionization degree of PAHs, increase linearly with the above-mentioned *IRAS* colors and the *AKARI* color of S_{24}/S_{11}, which are sensitive to massive star-formation activities (see Fig. 1). Under such quiescent environments as those associated with Group A members, the size distribution of PAHs does not change considerably (Micelotta et al., 2011). Thus the observed trend indicates that PAHs are heated to higher excitation temperatures and their ionization fraction increases as the incident radiation field becomes harder and stronger. However, the ratios of the other three positions, which are associated with OB star clusters within HII regions N158 and N159 (Nakajima et al., 2005) and whose spectra show ionization signatures (classified into Group B), do not follow the sequence (Fig. 1). It can be attributed to the destruction of small-sized PAHs by electron collisions and enhanced recombination of electrons due to a large increase in the electron density inside HII regions.

2.3. Diagnostic Diagram

Taking advantage of the relationship between PAHs and incident radiation conditions suggested by the results, we propose a combination of the UIR MIR bands with the UIR 3.3 μm band as an efficient diagnostic tool for interstellar radiation conditions, in which interstellar radiation conditions are estimated from the ionization degree of PAHs and the size distribution of PAHs. Fig. 2 shows the observed band ratios plotted together with model calculations on the diagram

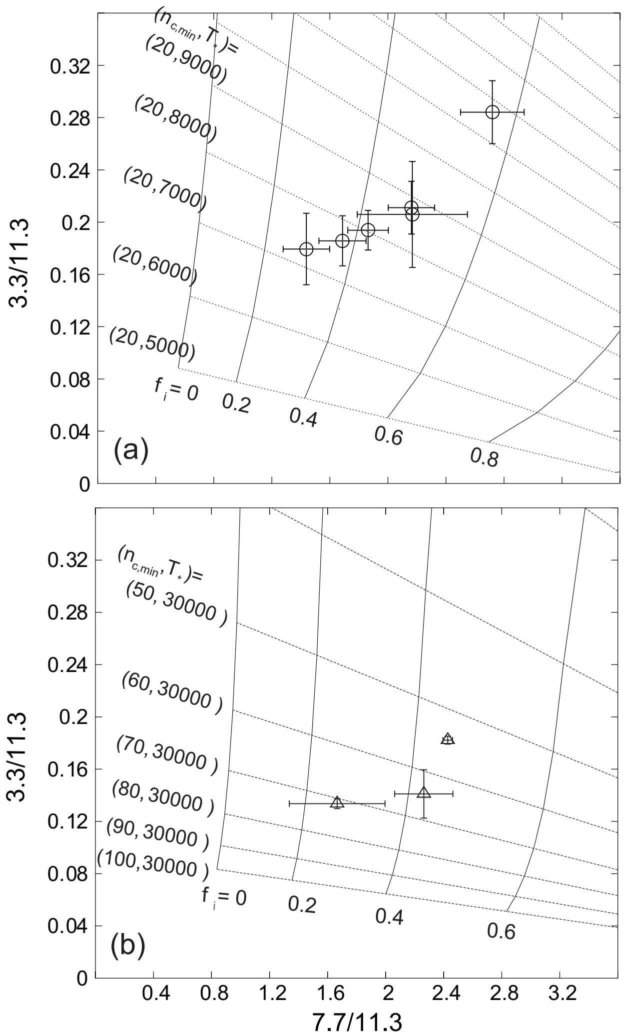

Fig. 2. A diagnostic diagram of $I_{3.3}/I_{11.3}$ versus $I_{7.7}/I_{11.3}$. In the upper panel (a), Group A members are plotted as open circles together with model calculations. In the calculation, we assume a quiescent environment where the size distribution of PAHs does not change and the minimum size of PAHs is set as those with the number of carbon atoms, $n_{\rm C} = 20$. The band ratios vary according to the ionization degree of PAHs, $f_{\rm i}$, and the effective temperature of the heating source, T_*. In the lower panel (b), Group B members are plotted as open triangles together with the model results, in which the minimum size is varied from $n_{\rm C} = 50$ to 100 and T_* is fixed as 30000 K. We find that the results do not depend on T_* for T_*=20,000–50,000 K because of the Lynman cut-off. See Mori et al. (2012) for details of the model calculation.

of $I_{3.3}/I_{11.3}$ versus $I_{7.7}/I_{11.3}$. These model calculations demonstrate that the ratio of $I_{3.3}/I_{11.3}$ is very sensitive to the effective temperature of the heating source, T_*, or the number of carbons of the smallest PAH, $n_{\rm C,min}$, that is, the excitation temperature of PAHs.

3. COMPARISON WITH OTHER GALAXIES

To examine whether the relationship between PAHs and incident radiation conditions suggested by the LMC results could be applied to other objects, we investigate the PAH properties in the nearby late-type spiral galaxy NGC 6946, the nearby whirlpool galaxy M51, and the nearby barred galaxy NGC 1313, and compare them to those in the LMC (see Fig. 1).

The NIR and MIR slit spectroscopic observations have been carried out on NGC 6946, M51, and NGC 1313 with *AKARI*/IRC as well as the LMC. However, for NGC 6946 and NGC 1313, only one pointing observation has been done. In the NGC 6946 observation, the slit is laid around the spiral arm of NGC 6946 (see Sakon et al. (2007) for MIR imaging and spectroscopic observations with the *AKARI*/IRC). We extract spectra from two positions within a slit area of $5'' \times 1'$, where star formation activity is supposed to be low (Position 1) and moderate (Position 2). In the NGC 1313 observation, the slit is located at the active star-formation region within the arm of NGC 1313, from which the spectrum is extracted. Within the M51 system, two pointing observations have been performed and we extract spectra from three positions. Position 1 and 2 are the spiral arm and inter-arm region of the host galaxy M51a, and Position 3 is on the interacting tail of the satellite galaxy M51b.

As shown in Fig. 1, the relationship observed in the LMC seems to not always hold in other galaxies. The observed scatter suggests that what affects PAH properties is not only on-going star-formation activities, but also intrinsic properties of galaxies (e.g., metallicity, star-formation history and so on). In particular, the highest band ratio of $I_{3.3}/I_{11.3}$ is observed in the active star-forming region of NGC 1313, while the lowest band ratio is seen in the moderate star-forming region in NGC 6946. The $I_{3.3}/I_{11.3}$ ratio has large diversity among galaxies, and so the combination of the 3.3 μm band with the MIR bands may be a clue to unveil interstellar conditions of galaxies. The number of the observed data points is still too small to reach a general conclusion at present. Further investigation is needed on various astronomical objects for deeper understanding.

ACKNOWLEDGEMENTS

This work is based on observations with *AKARI*, a JAXA project with the participation of ESA. We appreciate all the members of the *AKARI* project and the members of the Interstellar and Nearby Galaxy team for their help and continuous encouragement. This work is supported in part by a Grant-in-Aid for Scientific Research from the Japan Society of Promotion of Science (JSPS).

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