Properties of UIR bands in NGC6946 based on mid-infrared observations with Infrared Camera on board *AKARI*

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ABSTRACT

We present our latest results on the mid-infrared imaging and spectroscopy of the nearby late-type spiral galaxy NGC6946 with the Infrared Camera (IRC) on board *AKARI*. Based on the mid-infrared imaging with the S7(7μm) and S11(11μm) bands, we find larger S7/S11 ratio in the arm region than in the interarm region. We have investigated the UIR band spectrum of a star forming region located on the arm of NGC6946 as well as that of its outside. We find that the relative band strengths of the UIR 6.2, 7.7, and 8.6μm bands to the 11.2μm band are larger in the star forming region located on the arm than its outside even if the interstellar extinction of $A_V = 3$mag towards the star forming region is taken into account. The present result suggests that the ratios of 6.2μm/11.2μm, 7.7μm/11.2μm, and 8.6μm/11.2μm can be used as direct and efficient tools to measure the on-going star formation activity in remote galaxies.

Subject headings: galaxies: ISM — infrared: ISM — ISM: dust, extinction

1. Introduction

The ubiquitous Infrared (UIR) bands are a series of distinct emission bands seen in the near- to mid-infrared spectra of various kinds of astrophysical objects (Tokunaga (1997) for a review), and are supposed to be carried by polycyclic aromatic hydrocarbons (PAHs) (Léger & Puget 1984; Allamandola, Tielens, & Barker 1985) and/or materials including PAH-like molecular groups. The carriers are excited by absorbing a single ultra-violet photon and

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release the energy with a number of infrared photons in cascades via several lattice vibration modes of aromatic C-H and C-C (Allamandola, Tielens, & Barker 1989). The ionization state of PAH molecules is one of the most significant factors to affect the spectral characteristics of the UIR features. Laboratory experiments as well as theoretical studies have shown that the band features in the 6–9μm region are much weaker than those in the 11–14μm region when PAHs are neutral, however, that they increase their strengths relative to those in the 11–14μm region when PAHs are ionized (de Frees et al. 1993; Szczepanski & Vala 1993; Bakes, Tielens, & Barker 2001). Several observational studies report that the variations in 7.7μm/11.2μm and/or 8.6μm/11.2μm within a reflection nebula along the distance from the central star (Bregman & Temi 2005; Joblin et al. 1996), among Herbig Ae/Be stars with different spectral types (Sloan et al. 2005) have been reasonably explained by the difference in the ionization status of the carriers of the UIR bands. In this proceedings, we focus on the variations in the UIR bands between in the arm region and in the inter-arm region of the nearby late-type spiral galaxy NGC6946 based on the recent observation with Infrared Camera (IRC) on board *AKARI*. This galaxy is characterized by heavy star formation activity throughout the disk (Sauty, Gerin, & Casoli 1998) and evidence of massive star clusters or a young globular clusters has been reported (Elmegreen, Efremov, & Larsen 2000; Larsen et al. 2002). NGC6946 is located at a distance of 5.9 Mpc (Karachentsev, Sharina, & Mathis 1989) and the pixel scale of 2.34" for *AKARI*/IRC Mid-infrared Short (MIR-S) channel (Onaka et al. 2007b) corresponds to about 70 pc at the distance of NGC6946. We discuss the effects of star forming activity in the galactic arm on the evolution of the carriers of the UIR bands in a galactic scale.

2. Observations

Two pointed observations of NGC6946 were executed at 20:23:51(UT) and 23:42:05(UT) on 20 June 2006 in the framework of instrument calibration time for the IRC. One pointed observation (observation ID:5124017) was performed with the spectroscopic mode (AOT04), in which the data were taken with two grisms, SG1 (5.4–8.4μm) and SG2 (7.5–12.9μm), installed in the MIR-S channel. The other one (observation ID:5124018) was performed with the two-filter imaging mode (AOT02), in which the data were taken with two medium band filters, S7 (5.9–8.4μm) and S11 (8.5–11.3μm), installed in the MIR-S channel (Onaka et al. 2007b). Each image has a wide field-of-view of about 10'$\times$10' and a pixel scale of the MIR-S channel is 2."34 (Onaka et al. 2007b). The position of the slit for spectroscopy with MIR-S channel is settled to ($\alpha_{J=2000}$,$\delta_{J=2000}$)=($20^h34^m51.3^s$,$+60^d07^m54^s$) which is located at $\sim$80" distant from the nucleus of the NGC6946 and the slit position is confirmed by the MIR-S/S9W image that was obtained during the observation sequence of the AOT04. The data reduction procedures are described in Sakon et al. (2007) and are basically consistent with those in the *IRC Imaging Pipeline Version 20070912* for Imaging observations and with those in the *IRC Spectroscopy Toolkit Version 20070913* (Ohyama et al. 2007) for spectroscopic observations.

3. RESULTS

The results of the mid-infrared imaging observations of NGC6946 taken with the *AKARI* IRC MIR-S/S7 and S11 bands are shown in Fig. 1a and b, respectively. A number of infrared sources are found in each image and many of them are supposed to be massive star forming regions (Georgelin & Georgelin 1976; Tacconi & Young 1990). They are distributed forming in arm-like patterns, which correspond to the optical arms of NGC6946 reported by Tacconi & Young (1990). The S7/S11 color map of NGC6946 is shown in Fig. 1c and we find the S7/S11 ratio in the arm regions is typically larger than unity while those in the interarm region are typically smaller than unity. The slit for spectroscopy with the *AKARI* IRC/MIR-S is located so that it crosses both the arm region and the interarm region of NGC6946 (See Fig. 2). The length of the slit is 40" and we succeeded in obtaining both the spectra of the interarm and the arm regions, the latter of which includes the HII region candidate of LDG source 47 located at (α_{J2000},δ_{J2000})=($20^h34^m50^s.80$, $+60^d07^m48^s.9$) (Hyman et al. 2000; Lacey, Duric, & Goss 1997). The obtained spectra at the arm and interarm positions are shown in Figs. 3a and 3b, respectively. Note that the spectra of zodiacal emission are not removed in both spectra. We obtain the spectrum of the HII region candidate LDG source 47 by simply subtracting the spectrum at the interarm region (Fig. 3b) from that at the arm region (Fig. 3a) and the result spectrum is shown in Fig. 3c. Note that the LDG source 47 spectrum is not an independent data set from the arm spectrum, but simply highlights the difference between the arm and interarm spectra. In order to evaluate the variations in the relative band strengths of the UIR features, we define local continuum baselines where the data points near 6.0, 6.5, 7.2, 8.2, 8.8, 10.9 and 11.7μm are chosen as the continuum points. The strengths of the UIR features for LDG source 47, the arm region, and the interarm region are summarized in Table. 1. Since the relative band strengths of the UIR bands can be affected by the silicate absorption feature centered at 9.7μm, we assume an extinction ratio of $A_V/\tau_{9.7\mu m} = 18.5 \pm 1.5$ (Roche & Aitken 1984) and examined the effect of extinction by astronomical silicate (Draine & Lee 1984) on the UIR relative band strengths. Ferguson, Gallagher, & Wyse (1998) have obtained optical spectra of HII regions in NGC6946 and have reported that the visual extinction toward HII regions located even in the vicinity of the galactic center of NGC6946 is less than 3 mag. Hyman et al. (2000) also report a visual extinction of $A_V = 1.0 \pm 1.2$ toward LDG HII region candidates including LDG source 47 based on the comparison between the radio and optical measurements. In the following analysis, we adopt a visual extinction of $A_V = 3$ mag to correct the extinction effects on the UIR band strengths in the spectra of LDG source 47 and the arm region. The relative band strengths of the UIR 6.2μm/11.2μm, UIR 7.7μm/11.2μm, and UIR 8.6μm/11.2μm corrected for extinction are listed in Table 2. If we try to attribute the difference in the ratio of UIR 6.2μm/11.2μm between the arm and interarm regions solely to the extinction effect, a visual extinction of $A_V = 18.7$ mag for the arm region is required even if we assume no extinction for the interarm region, which is too large and far from those values obtained from previous studies. Therefore, we can conclude that the ratios of UIR 6.2μm/11.2μm and UIR 7.7μm/11.2μm of LDG source 47 are significantly larger than those of the interarm region by a factor of more than 2. The ratio of the UIR 8.6μm/11.2μm of LDG source 47 is also seem to be larger than that of the interarm region but the UIR 8.6μm feature is the weakest among the four UIR bands the difference in this band ratio is only significant at the 1-σ level.

4. DISCUSSION

Sakon et al. (2004) reported that the UIR band ratios of 6.2μm/11.2μm and 7.7μm/11.2μm in the diffuse Galactic emission for two directions in the inner Galactic plane of $|b| < 4^\circ.0$ (Areas I & II; $-12^\circ < l < -4^\circ$ and $44^\circ < l < 52^\circ$, respectively) are systematically larger than those for two directions in the outer Galactic plane of $|b| < 4^\circ.0$ (Areas III & IV; $-136^\circ < l < -128^\circ$ and $168^\circ < l < 176^\circ$, respectively) based on the observation with IRTS/MIRS. Their results may be closely related to those obtained for NGC6946. Towards the direction of the inner Galactic plane, multiple Galactic arms and star forming regions are supposed to be superposed on a line of sight, while smaller contributions from star forming regions and galactic arm structures are expected towards direction of the outer Galactic plane. Therefore, the reported variations in the UIR band ratios of 6.2μm/11.2μm and 7.7μm/11.2μm in the diffuse Galactic emission on a galactic scale reported should probably be explained by the higher average star forming activity in arms compared to the interarms of our Galaxy. A close relationship between the presence of the UIR bands and the star-forming activities are discussed in Peeters, Spoon, & Tielens. (2004), in which they claim that the UIR bands can be used as valid tracer of PDR regions mainly around B-type stars. Since the strengths of the UIR feature themselves are strongly dependent on the metallicity (O'Halloran, Satyapal, & Dudik 2006) and the past star formation histories in a galaxy, the present result suggests that the relative band strengths of the UIR 6.2, 7.7, and 8.6μm to 11.2μm features can be used as a more useful and vigorous measure of the extent of on-going

Table 1. The UIR features in NGC6946.

Region ID	Interarm Region[a]	Arm Region[b]	LDG source 47[b]
UIR 6.2μm(10^{-17}Wm^{-2}pix^{-1})	1.35±0.14	3.61±0.14	2.26±0.20
UIR 7.7μm(10^{-17}Wm^{-2}pix^{-1})	3.63±0.18	8.84±0.21	5.21±0.24
UIR 8.6μm(10^{-17}Wm^{-2}pix^{-1})	0.80±0.20	1.38±0.20	0.58±0.28
UIR 11.2μm(10^{-17}Wm^{-2}pix^{-1})	1.60±0.15	2.48±0.15	0.88±0.21
UIR 6.2μm/11.2μm	0.84±0.14	1.33±0.13	2.36±0.64
UIR 7.7μm/11.2μm	2.27±0.32	3.32±0.35	5.51±1.44
UIR 8.6μm/11.2μm	0.50±0.14	0.56±0.09	0.66±0.28

[a]No extinction correction are undertaken for the extreme case

[b]Extinction of $A_V = 3$ mag is taken into account.

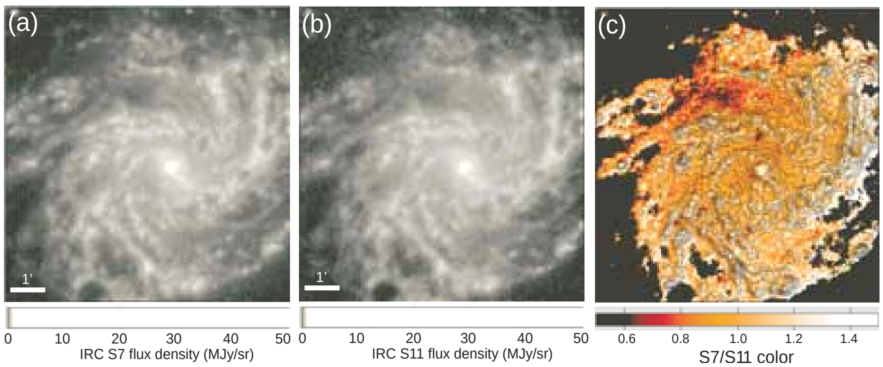

Fig. 1.— (a),(b) Mid-infrared images of NGC6946 taken with *AKARI* IRC/MIR-S/S7 and S11 bands, respectively. Image size is 8 by 8 arcmin^2. The S7/S11 ratio map of NGC6946. The contour indicates the intensity of *AKARI* IRC/MIR-S/S7. Levels are set as $2^{(n+1)/2}$ (MJy/sr).

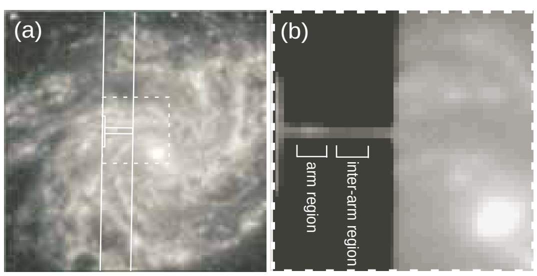

Fig. 2.— (a) Schematic slit position for mid-infrared spectroscopy with *AKARI*/IRC SG1 and SG2 overlaid with the S7 image of NGC6946. (b) Detailed image of slit position taken with *AKARI*/IRC S9W band in the same pointed observation for the spectroscopy.

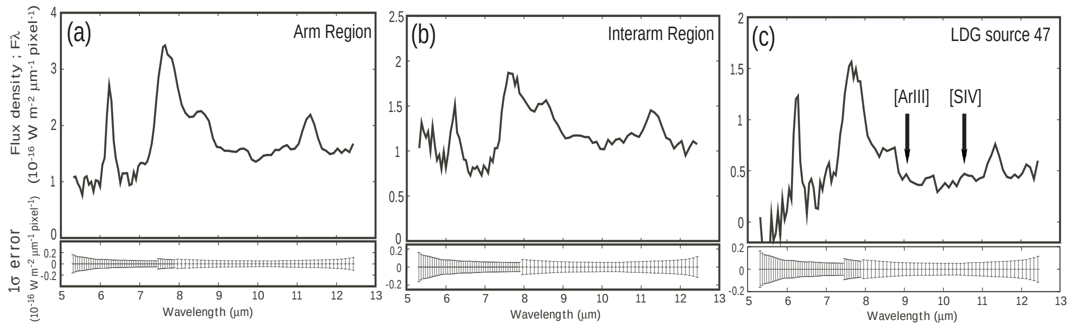

Fig. 3.— Obtained mid-infrared spectra of (a) the arm region, (b) the inter-arm region and (c) the massive star forming region LDG source 47 on the slit for spectroscopy with *AKARI* IRC/MIR-S.

star forming activities in remote galaxies rather than the presence or absence of the UIR features.

The energy fractions of the UIR bands in the S7 and in S11 bands are estimated for the spectrum of LDG source 47 using the system spectral response curves. We found 40.5($\pm$3.8)% of the energy in S7 comes from the UIR 6.2μm and 7.7μm features and 7.7($\pm$1.0)% in S11 from the UIR 11.2μm feature. Therefore, the imaging data of S7 is expected to be quite sensitive to the variations in the strengths of the UIR 6.2 μm and 7.7μm features. The imaging data of S11 is dominated by the hot dust continuum emission from very small grains (VSGs) and is not sensitive to the strength of the UIR 11.2μm feature. The strength of the hot dust continuum around 12μm relative to the total far-infrared emission (FIR) stays almost constant over a wide range of radiation field strengths (Sakon et al. 2006; Onaka et al. 2007a) and the slit spectroscopic analysis suggests that the enhanced photoionization of PAHs and the increasing abundance of small free-flying PAHs in star forming regions of NGC6946. Therefore, the larger S7/S11 ratio in galactic spiral arm regions may be explained by the increase in strengths of the UIR 6.2μm and 7.7μm features as a result of the accelerated photoionization of PAHs in the arm regions of NGC6946.

5. SUMMARY

Based on the mid-infrared imaging obervations of the nearby late-type spiral galaxy NGC6946 with the S7 and S11 bands of Infrared Camera (IRC) on board *AKARI*, the S7/S11 ratios have larger values in the galactic arm than in the interarm region of NGC6946.

Since over 40% of the energy in the S7 band is dominated by the UIR 7.7μm and 6.2μm features, the variations in the S7/S11 ratio between the galactic arm and the interarm of NGC6946 are supposed to be strongly affected by the variations in the strengths of the UIR 7.7μm and 6.2μm features relative to the hot dust continuum emission. We performed the slit spectroscopy of both the HII region candidate LDG source 47 in the galactic arm and the interarm of NGC6946 . We find clear variations in the relative band strengths of these features such that the ratios of 6.2μm/11.2μm, 7.7μm/11.2μm, and 8.6μm/11.2μm have larger values in the galactic arm region and in LDG source 47 than in the interarm region even if the interstellar extinction of $A_V = 3$mag is assumed. The increase in the UIR 6.2μm and 7.7μm features relative to the 11.2μm feature is consistent with the ionization of PAHs in the star forming region. The present study also suggests that the ratios of 6.2μm/11.2μm, 7.7μm/11.2μm, and 8.6μm/11.2μm may be used as direct and efficient tools to estimate the on-going star formation activity in remote galaxies in addition to the presence-or-absence appearance of the UIR bands.

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