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PROCESSING OF INTERSTELLAR MEDIUM AS DIVULGED BY AKARI

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ABSTRACT

A wide spectral coverage from near-infrared (NIR) to far-infrared (FIR) of *AKARI* both for imaging and spectroscopy enables us to efficiently study the emission from gas and dust in the interstellar medium (ISM). In particular, the Infrared Camera (IRC) onboard *AKARI* offers a unique opportunity to carry out sensitive spectroscopy in the NIR (2–5 μm) for the first time from a spaceborn telescope. This spectral range contains a number of important dust bands and gas lines, such as the aromatic and aliphatic emission bands at 3.3 and 3.4–3.5 μm, H_2O and CO_2 ices at 3.0 and 4.3 μm, CO, H_2, and H I gas emission lines. In this paper we concentrate on the aromatic and aliphatic emission and ice absorption features. The balance between dust supply and destruction suggests significant dust processing taking place as well as dust formation in the ISM. Detailed analysis of the aromatic and aliphatic bands of *AKARI* observations for a number of H II regions and H II region-like objects suggests processing of carbonaceous dust in the ISM. The ice formation process can also be studied with IRC NIR spectroscopy efficiently. In this review, dust processing in the ISM divulged by recent analysis of *AKARI* data is discussed.

Key words: infrared: ISM — ISM: general — ISM: dust

1. INTRODUCTION

Dust grains play significant roles in physical and chemical processes in the interstellar medium (ISM) and their lifecycle is a key to understanding the evolution of the ISM (e.g., Onaka, 2012). Dust is formed in stellar winds or supernova explosions, migrating to interstellar clouds after having been processed in the ISM, and taken in by newly born stars. The dust supply from stellar sources is predicted to be dominated by supernovae. However until the recent detection of a significant amount of dust ($> 0.2M_\odot$) in the ejecta of SN 1987A (Matsuura et al., 2011; Indebetouw et al., 2014), little evidence had been obtained for the production of a large amount of dust in SNe (e.g., Gall et al., 2011). While an appreciable amount of dust in ejecta has so far been found for a handful of supernova remnants by recent infrared observations (Sibthorpe et al., 2010; Barlow et al., 2010; Gomez et al., 2012), the actual amount of dust formed in SNe is still an open question. Even assuming that all condensible elements form dust grains in SNe, however, the dust supply from stellar sources is likely to be outstripped by the dust destruction by SN shocks, suggesting that a large fraction of interstellar dust must be forming in dense regions in the ISM (Jones & Nuth, 2011). Processing of dust grains in the ISM and dense clouds is, therefore, a key for the understanding of the dust lifecycle.

Emission from dust grains dominates in the infrared and infrared observations provide the most efficient means to investigate dust processing. *AKARI* has a wide spectral coverage from the near-infrared (NIR) to far-infrared (FIR) in imaging and spectroscopy (Murakami et al., 2007), which enables us to study the properties of dust grains together with gas in the ISM. In particular, the Infrared Camera (IRC) onboard offers a unique opportunity to carry out sensitive spectroscopy in the NIR for the first time from space even after the exhaustion of the cryogen (Onaka et al., 2007, 2010; Ohyama et al., 2007). The NIR spectral range (2–5 μm) contains a number of interesting dust bands and gas lines, including the aromatic and aliphatic emission bands at 3.3 and 3.4–3.5 μm, H_2O and CO_2 ice absorption bands at 3.0 and 4.3 μm, and CO, H I, and H_2 emission lines (Onaka, 2013, and also see Figure 3). In this paper, we concentrate on the solid features and present an overview for the recent studies of interstellar dust processing revealed by IRC NIR spectroscopy.

2. PROCESSING OF CARBONACEOUS DUST

Jones et al. (2013) propose an interesting scenario for the evolution of carbonaceous dust grains, where they predict that carbonaceous dust tends to be aromatized in the ISM by the interstellar radiation and aliphatic C-H bonds are converted into aromatic C-H particularly for very small grains. Mori et al. (2014a) study more than 160 lines of sight towards 36 Galactic H II regions and H II region-like objects with IRC NIR spectroscopy and derive the intensities of the emission bands originating from aromatic bonds at 3.3 μm and aliphatic bonds for 3.4–3.5 μm. The variation of the band ratio of aliphatic to aromatic bonds $I(3.4-3.5\,\mu\mathrm{m})/I(3.3\,\mu\mathrm{m})$ is detected and found to be correlated with the ratio of the continuum intensity at 3.7 μm to the 3.3 μm band intensity $I_c(3.7\,\mu\mathrm{m})/I(3.3\,\mu\mathrm{m})$ (Figure 1). The continuum intensity at 3.7 μm is derived after subtracting the contribution from free-free emission and is supposed to come from ionized band carriers (Haraguchi et al., 2012), while the 3.3 μm emission comes from neutral carriers. Thus the ratio of the 3.7 μm to 3.3 μm intensity indicates the fraction of the ionized carriers. The trend seen in Figure 1 suggests that the number of aliphatic bonds decreases relative to that of aromatic bonds with the increase of the ionization fraction, being in agreement with the theoretical prediction by Jones et al. (2013). The relative number of bay to non-bay hydrogen in the band carriers also shows a correlation with the 3.4 to 3.3 μm band ratio (Hammonds et al., 2014), suggesting

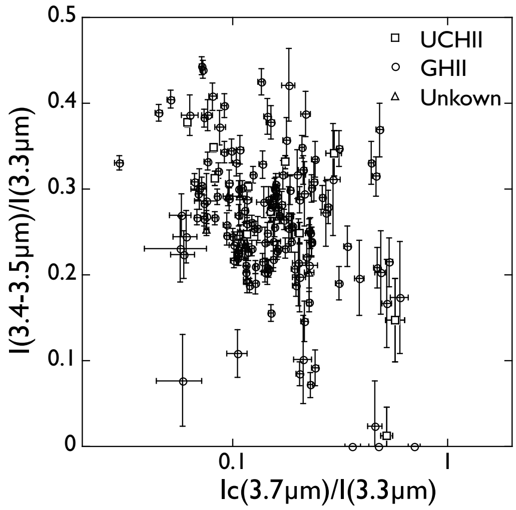

Figure 1. Plot of the aliphatic to aromatic band intensities $I(3.4-3.5\,\mu\mathrm{m})/I(3.3\,\mu\mathrm{m})$ against the ionization fraction indicator $I_c(3.7\,\mu\mathrm{m})/I(3.3\,\mu\mathrm{m})$. See text for details.

that the processing is also associated with the variation in the structure of the carriers. *AKARI* observations clearly show the variation of features from the carbonaceous grains in the ISM for the first time.

3. SEARCH FOR EMISSION FEATURES FROM DEUTERATED PAHs

Ultraviolet observations indicate that interstellar deuterium is largely depleted ($\leq 30\%$) compared to model predictions and the depletion shows a good correlation with the depletion of metal elements (Linsky et al., 2006). It is then suggested that the depleted deuterium could reside in interstellar polycyclic aromatic hydrocarbons (PAHs), which are thought to be responsible for several emission bands from NIR to MIR (Draine, 2006). The emission bands at 3.3 and 3.4 μm from C-H bonds are expected to shift to around 4.4 and 4.6 μm, respectively, if hydrogen is replaced by deuterium. ISO observations detected these bands at a marginal level towards the Orion bar and M17 (Peeters et al., 2004). However, recent observations with *AKARI* IRC could not confirm the presence of the features from deuterated PAHs (PADs) (Onaka et al., 2014). As indicated in Figure 2, there is excess emission remaing in 4.4–4.6 μm, some of which can be attributed to known species. With the low spectral resolution of the IRC spectroscopy it is difficult to make unambiguous identification of those faint features and the remaining excess gives us an upper limit for the PAD to PAH band ratio of 3%. The difference in the band oscillator strength is compensated by

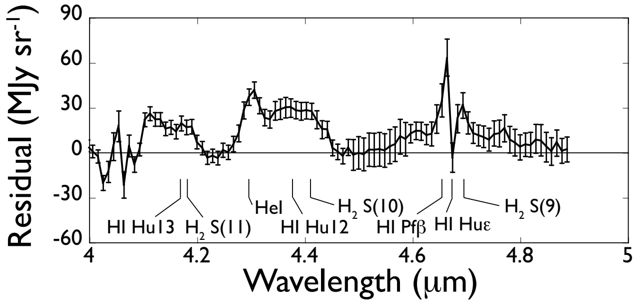

Figure 2. Residual spectrum of the Orion bar taken with *AKARI* IRC after subtraction of the continuum and expected emission from ionized gas. The location of known features are indicated. See Onaka et al. (2014) for more details.

the difference in the excitation conditions and the band ratio is nearly equal to the abundance ratio under the standard conditions (Onaka et al., 2014). We further look for the PAD features in a larger sample and find that the largest excess emission detected in this spectral range is 6% relative to the 3.3–3.5 μm band intensities. It should be noted that as described above, the excess emission could arise from species other than PADs and this only gives an upper limit for the PAD to PAH ratio. The upper limit is still too small to explain the amount of depleted deuterium. Since the NIR emission comes from the smallest PAHs, it cannot be ruled out that the depleted deuterium hides in larger PAHs.

4. INTERSTELLAR ICES

ISO and Spitzer observations show that the column densities of CO_2 and H_2O ices are linearly correlated and the slope of the linear correlation for massive young stars and quiescent interstellar clouds is lower (~ 0.17) than that for low-mass young stars of about 0.32 (Nummelin et al., 2001; Whittet et al., 2007; Pontoppidan et al., 2008). The good linear correlation suggests that CO_2 and H_2O ices are formed in tandem via no-energy barrier reactions on dust grains (Oba et al., 2010; Ioppolo et al., 2011). The different slope of the linear correlation in massive YSOs in the LMC further suggests a dependence of the formation process on the environmental conditions (Shimonishi et al., 2008, 2010). It is also shown that the column densities of CO_2 and H_2O ices in quiescent clouds show a good correlation with the visual extinction with a threshold of $A_\mathrm{v} = 4.3 \pm 1.0$ mag for the presence of ices (Whittet et al., 2001, 2007).

We investigate CO_2 and H_2O ice absorption features at 4.3 and 3.0 μm in the present sample. About 80 line-of-sight data are analyzed in the present paper and more are discussed in Mori et al. (2014b). Typical spectra of the sample are shown in Figure 3. We use a SPLINE fit to estimate the continuum and derive the ice column densities. As suggested in Figure 3, however, it is not straightforward to draw a continuum line because of the emission bands at 3.3–3.5 μm. It should be borne in mind that the column density of H_2O ice depends on the assumed continuum.

Figure 4 shows the correlation between CO_2 and H_2O ice column densities. It shows a good correlation and the slope is in between 0.12 and 0.17, being consistent with previous results (Pontoppidan et al., 2008). The *AKARI* data further support the concurrent formation of the two ices. It should be noted that there are several data points below the correlation line in the low column density region. This may suggest sublimation of CO_2 ice over H_2O ice because of the lower sublimation temperature of CO_2. Careful investigation on the effect of the continuum is needed to confirm the results.

Figure 5 shows the correlation of the ice column densities with the ratio of the H I recombination lines of Brβ to Brα. Case B conditions with the electron density of $10^4\,\mathrm{cm}^{-2}$ and the temperature of 10^4 K give the ratio of about 0.58 (dotted line). There may be an upper limit of the ratio in the present sample indicated by the dashed line, which corresponds to $A_\mathrm{v} \sim 5$.

5. SUMMARY

IRC NIR spectra contain significant information on the interstellar medium. Detailed studies of the 3.3–3.5 μm emission features in the ISM have revealed the processing of small carbonaceous dust for the first time, suggesting the preferential aromatization and a possible structural change. A preliminary search for the deuterated PAH features in a large sample suggests an upper limit of PAD to PAH as 6% and further investigations are needed to identify the place of the depleted deuterium. A study of the CO_2 and H_2O absorption features in a large number of lines of sight confirms the linear correlation between their column densities, further supporting the concurrent formation of these ices in the ISM. It also suggests a hint of sublimation of CO_2 ice in warm regions. *AKARI* observations are about to divulge the processing and lifecycle of dust in the ISM.

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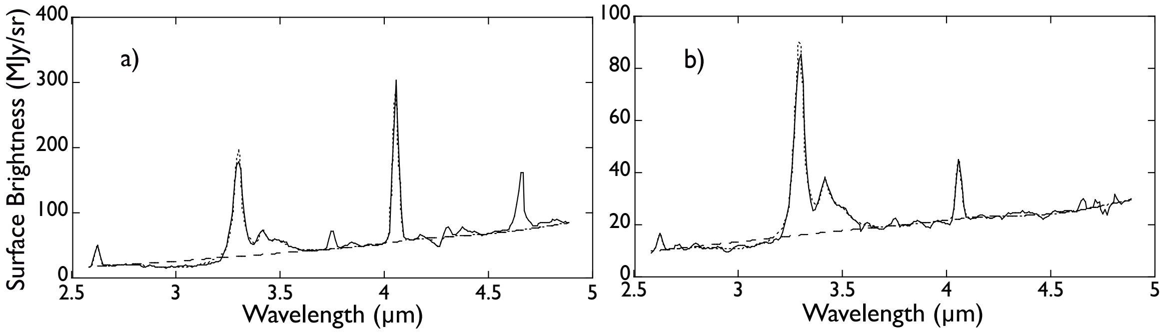

Figure 3. Typical spectra of the present sample. (a) spectrum with H_2O and CO_2 absorption and (b) spectra with weak H_2O absorption without CO_2 absorption. The solid lines show observed spectra, the dotted lines indicate fitted spectra, and the dashed lines are assumed continuum.

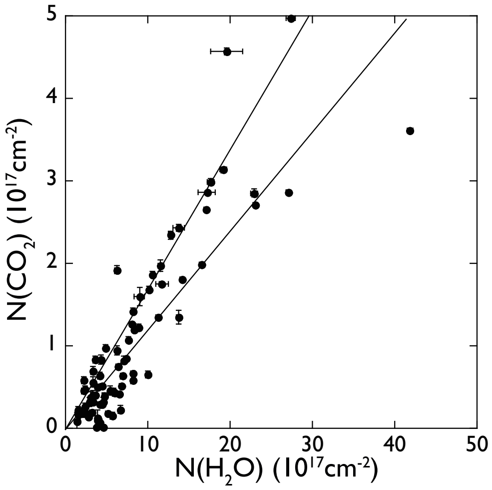

Figure 4. Correlation of the column densities of CO_2 and H_2O ices for the present sample. The solid lines with the slopes of 0.17 and 0.12 are indicated as reference, in between which most data points reside (see text).

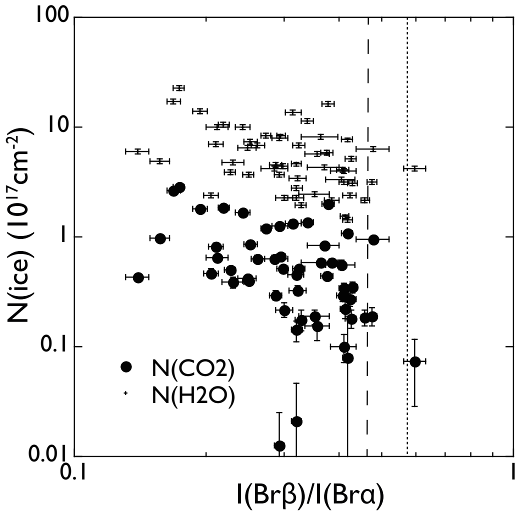

Figure 5. Correlation of the ice column densities and the ratio of Brβ to Brα line intensities. The pluses indicate H_2O ice, while the filled circles show CO_2 ice. The dotted line indicates the ratio for Case B with the electron density of $10^4\,\mathrm{cm}^{-2}$ and the temperature of $10^4\,\mathrm{K}$. The dashed line suggests a possible upper limit of the present sample, which corresponds to $A_\mathrm{v} \sim 5$.

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