DIFFERENCE IN THE SPATIAL DISTRIBUTION BETWEEN H₂O AND CO₂ ICES IN M 82 FOUND WITH AKARI

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ABSTRACT

With AKARI, we obtain the spatially resolved near-infrared (NIR) (2.5–5.0 μm) spectra for the nearby starburst galaxy M 82. These spectra clearly show absorption features due to interstellar ices. Based on the spectra, we created the column density maps of H₂O and CO₂ ices. As a result, we find that the spatial distribution of H₂O ice is significantly different from that of CO₂ ice; H₂O ice is widely distributed, while CO₂ ice is concentrated near the galactic center. Our result reveals for the first time variations in CO₂/H₂O ice abundance ratio on a galactic scale, suggesting that an ice-forming interstellar environment changes within a galaxy. We discuss the cause of the spatial variations in the ice abundance ratio, utilizing spectral information on the hydrogen recombination Brγ and Brβ lines and the polycyclic aromatic hydrocarbon 3.3 μm emission appearing in the AKARI NIR spectra.

Key words: galaxies: individual (M 82) – galaxies: ISM – infrared: galaxies – ISM: molecules

Online-only material: color figures

1. INTRODUCTION

Absorption features due to interstellar ices are observed in near-infrared (NIR) and mid-infrared spectra of the interstellar medium (ISM). Generally, ices are formed on the surface of dust in dense molecular clouds (T ∼ 10 K, nH ∼ 10⁶ cm⁻³), forming ice mantles. In an NIR spectrum, we can observe deep absorption features particularly due to H₂O ice at 3.05 μm and CO₂ ice at 4.27 μm. These interstellar ices contain much information on the interstellar environment. Among various ices, CO₂ ice is one of the most important as a probe of the interstellar environment. That is because CO₂ ice is a secondary product unlike H₂O and CO ices which are primarily formed on dust grains. The formation process of CO₂ ice, indicated by the recent model and experimental analyses (Garrod & Pauly 2011; Noble et al. 2011), is as follows:

\[ \text{CO} + \text{OH} \rightarrow \text{CO}_2 + \text{H}. \]  

(1)

Related to the formation process, both energetic and non-energetic processes are proposed. As an energetic process, Watanabe & Kouchi (2002) showed that CO₂ ice is produced from a H₂O–CO ice mixture by UV radiation, based on the laboratory experiments. Alternatively, Obu et al. (2010) experimentally demonstrated a non-energetic process, in which the abundance of CO₂ ice varies with dust temperature since the process is a grain surface reaction and a high dust temperature changes the mobility of the OH radical. Thus, these processes suggest that the abundance of CO₂ ice may have information on the UV radiation environment or the dust temperature. Additionally, ices have different sublimation temperatures (e.g., 90 K and 50 K for H₂O and CO₂, respectively; Tielens 2005). Therefore we can estimate the thermal history of dust from the presence or absence of ices.

Hence, interstellar CO₂ ice is a useful tracer of the interstellar environment. However, studies of CO₂ ice, especially in nearby galaxies, have not yet been intensively performed because CO₂ ice is not observable with ground-based telescopes due to the atmospheric absorption. The detections of CO₂ ice in our Galaxy are reported for some young stellar objects (Gibb et al. 2004) and several regions of the diffuse ISM (e.g., Taurus: Bergin et al. 2005, Ophiuchus: Teixeira & Emerson 1999, and IC 5146: Chiar et al. 2011). With the Infrared Space Observatory, Spoon et al. (2000) detected the absorption features due to H₂O, CO₂, CO, and XCN ices in the nearby galaxy NGC 4945. These previous observations were performed only for discrete spots. In order to investigate CO₂ ice more effectively, it is valuable to perform mapping observations of ices on a large scale.

Spectroscopy with the AKARI/Infrared Camera (Murakami et al. 2007; Ohyama et al. 2007) enables us to efficiently study ices in the NIR (2.5–5.0 μm), which is unique in terms of continuously covering the wavelength range with high sensitivity. Yamagishi et al. (2011) showed the NIR spectra with H₂O and CO₂ ices in the central ~600 pc region of NGC 253; the spatial distribution of H₂O ice is found to be similar to that of CO₂ ice. In this paper, we present the result for M 82. Using the NIR spectra of M 82, Yamagishi et al. (2012) previously discussed variations of the polycyclic aromatic hydrocarbon (PAH) 3.3 μm feature and the aliphatic sub-features at 3.4–3.6 μm in the galactic disk and halo regions. Here we focus on H₂O and CO₂ ices to investigate their spatial distribution in the central ~1 kpc region. Unlike the case of NGC 253, we clearly reveal the difference in the spatial distribution between H₂O and CO₂ ices, which gives physical implications for the ice-forming interstellar environment in M 82.

2. OBSERVATIONS AND DATA REDUCTION

In all the observations, we used a grism spectroscopic mode (Ohyama et al. 2007) to obtain 2.5–5.0 μm spectra. A summary of the observations and sub-slit apertures used in the present study is listed in Table 1, where regions A, B, and C are those defined in Yamagishi et al. (2012), covering the central ~1 kpc region at a distance of M 82 (3.53 Mpc; Karachentsev et al.
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2. OBSERVATIONS AND REDUCTION

2.1. Summary of the Observations and Sub-slit Apertures Used in the Present Study

We shifted the slit sub-aperture position by 1 pixel and derived a spectrum from each sub-aperture. Two independent observations were performed for region A, and the two spectra are combined to improve the S/N (S/Ns) ratio. The basic reduction processes are the same as those in Yamagishi et al. (2012). Depending on the signal-to-noise ratios (S/Ns), we divided the slit aperture area into sub-apertures as listed in Table 1, and derived a spectrum from each sub-aperture. We shifted the slit sub-aperture position by 1 pixel (1′′46) one after the other to consecutively derive spectra along the slit. Two independent observations were performed for region A, and the two spectra are combined to improve the S/N. Finally, smoothing with a boxcar kernel of ~0.03 μm was applied to each spectrum. As a result, we extract 77 spectra in total. We consider errors given by the pipeline plus wavelength-dependent background noise; the latter errors are evaluated as 1σ standard deviations every 0.2 μm wavelength range for 82 spectra of the blank sky.

Table 1
Summary of the Observations and Sub-slit Apertures Used in the Present Study

| Obs. Date     | ObsID     | Slit | Sub-aperture Size | Region |
|---------------|-----------|------|-------------------|--------|
| 2008 Oct 21, 22 | 3390001.1, 2 | Nh   | 3′′ × 4′′4        | A      |
| 2008 Oct 23    | 3390002.1 | Nh   | 3′′ × 7′′3        | C      |
| 2008 Oct 22    | 3390003.1 | Nh   | 3′′ × 7′′3        | B      |

2.2. Absorption Features

We have detected absorption features due to H2O ice, CO2 ice, the PAH 3.3 μm feature, aliphatic sub-features at 3.4–3.6 μm, Brα at 4.05 μm, Brβ at 2.63 μm, and Pfγ at 4.65 μm. The former and latter functions were used for H2O and CO2 ices, respectively. We used simple linear and Gaussian functions as possible. We used simple linear and Gaussian functions as possible. We used simple linear and Gaussian functions as possible. We used simple linear and Gaussian functions as possible. We used simple linear and Gaussian functions as possible.
In Figures 2(a) and (b), we also find a clear difference in the spatial distribution of the ices; H$_2$O ice is significantly detected in all the observed regions, while CO$_2$ ice is detected only in smaller areas near the galactic center. These trends are consistent with the changes of the spectra seen in Figure 1. In a previous study of the ices in NGC 253, there is no clear difference in the spatial distribution between H$_2$O and CO$_2$ ices (Yamagishi et al. 2011). Our result reveals for the first time variations in CO$_2$/H$_2$O ice abundance ratio on a galactic scale, suggesting that the ice-forming interstellar environment changes within a galaxy.

4. DISCUSSION

We quantitatively examine the relation between the abundance of the ices and the properties of the ISM using the spectral features in the NIR. Figure 3(a) shows the column densities of the total ice plotted against the PAH 3.3 $\mu$m feature intensity. The figure shows a rather loose correlation ($R = +0.61$ for independent 14 regions with significant detection of H$_2$O and CO$_2$ ices) as can also be expected from Figure 2. Thus, it reconfirms that the ices are not mainly present in PDRs. We also evaluate the amount of the ISM via the interstellar extinction. Figure 3(b) shows the abundance of the total ice plotted against Br$\beta$/Br$\alpha$ ratios and $A_V$. In the conversion from Br$\beta$/Br$\alpha$ ratios to $A_V$, we assume an extinction law in the NIR of $A_V \propto \lambda^{-1.85}$ (Landini et al. 1984), total-to-selective extinction ratio, $R_V$, of 3.1, and the intrinsic line ratio in Case B, temperature of $3 \times 10^4$ K, and electron density of $10^4$ cm$^{-3}$ (Storey & Hummer 1995). By using background stars for a dark cloud in our Galaxy, Whittet et al. (1988, 2007) reported a tight correlation between $A_V$ and column densities of the ices, which is also plotted in Figure 3(b). As can be seen in the figure, however, we find no clear correlation between them ($R = -0.29$ for independent 13 regions with significant detection of Br$\alpha$, Br$\beta$, H$_2$O ice, and CO$_2$ ice), which suggests that ice-forming clouds do not significantly contribute to obscuring the observed hydrogen recombination lines; the corresponding H$\textsc{ii}$ regions are likely to be located in the foreground of the ice-forming clouds. Then the column densities of the ices can be underestimated if the H$\textsc{ii}$ regions contribute to the continuum emission via free-free emission. Assuming that 50% of the continuum emission comes from the foreground, we confirm that the column densities of the both H$_2$O and CO$_2$ ices in each spectrum increase by factors of 2.1–2.4, but without significantly changing their relative abundances.

We examine the difference in the spatial distribution between H$_2$O and CO$_2$ ices. Figure 3(c) shows the CO$_2$/H$_2$O ice abundance ratios plotted against the PAH 3.3 $\mu$m intensities. In the figure, we find that there is a tight correlation between them ($R = +0.88$, $N = 14$). As shown in Figure 2, the spatial distribution of the PAHs has a sharp peak and monotonically decreases from the galactic center. Thus, the result suggests that the spatial distribution of the ices is clearly different between H$_2$O and CO$_2$ ices, and the abundance of CO$_2$ ice relative to H$_2$O

![Figure 2](image-url)
ice decreases significantly with the galactocentric distance. Here it is notable that the CO$_2$/H$_2$O ratios are strongly correlated with the PAH intensities, whereas the total ice column densities are not (Figure 3(a)), indicating that CO$_2$ ice is efficiently formed in the galactic center.

What causes the change in the CO$_2$/H$_2$O ice abundance ratios? Figure 3(d) shows the ice abundance ratios plotted against the PAH 3.3 $\mu$m/Br$\alpha$ flux ratios. In the figure, we find a negative correlation between the CO$_2$/H$_2$O ice abundance ratios and the PAH 3.3 $\mu$m/Br$\alpha$ ratios ($R = -0.78$, $N = 14$); the CO$_2$/H$_2$O ice abundance ratios are high in H$\!$ii-dominated regions, while they are small in PDR-dominated regions. Since the minimum photon energy to ionize hydrogen ($>13.6$ eV) is higher than that to excite PAHs ($<13.6$ eV), contribution from massive stars to the UV radiation field are likely to reflect the PAH 3.3 $\mu$m/Br$\alpha$ ratios. The result implies that massive stars are important to enhance the CO$_2$/H$_2$O ice abundance ratios. The galactic center of M 82 is indeed characterized by intense starburst (Westmoquette et al. 2007; Keto et al. 1999), which may cause the high CO$_2$/H$_2$O ice abundance ratios in the galactic center.

As for the formation processes of CO$_2$ ice, energetic processes are favorable in M 82 rather than non-energetic ones because CO$_2$ ice formation is enhanced by the intense radiation environment (Figure 3(d)). However, we should note that interstellar UV photons cannot penetrate into dense molecular clouds where ices are formed. Even in such a situation, UV photons can be induced by cosmic-rays penetrating deep inside clouds through their interactions with molecular hydrogen (Prasad & Tarafdar 1983). Although the acceleration process of cosmic-rays has not yet been fully understood, it is likely that many supernova remnants due to the starburst activities increase the cosmic-ray energy density in the galactic center. In fact, in our Galaxy, significant increases in cosmic-ray ionization rate are reported for several molecular clouds near the Galactic center and some supernova remnants (Goto et al. 2008; Indriolo et al. 2010; Indriolo & McCall 2012; Geballe & Oka 2010), which support our idea. In Figure 3(d), the data points for NGC 253 are also plotted against the PAH 3.3 $\mu$m/Br$\alpha$ ratios. From the figure, we find that they are distributed in a narrower range of the PAH 3.3 $\mu$m/Br$\alpha$ ratios than for M 82, which can explain why no significant variations in the CO$_2$/H$_2$O ice abundance
ratios were observed for NGC 253 (Yamagishi et al. 2011). Finally, for comparison with more intense starburst galaxies, we reanalyzed the AKARI NIR spectra of five (ultra)luminous galaxies (NGC 34, CGCG 436-030, ESO 507-G070, Arp 193, and Arp 220; Imanishi et al. 2010; Lee et al. 2012). The resultant CO2/H2O ice abundance and PAH 3.3 μm/Brα ratios are in ranges of 0.08–0.17 and 6.7–19.2, respectively, which follow the trend in Figure 3(d), but in similar ranges to those for M 82. This may suggest similarity in the hardness of the UV radiation field between M 82 and these galaxies as a whole.

5. CONCLUSIONS

With AKARI, we have obtained the spatially resolved NIR (2.5–5.0 μm) spectra for the nearby starburst galaxy M 82. We clearly detect spectral features due to H2O and CO2 ices, the PAH 3.3 μm feature, Brα, and Brβ. Based on the column density maps of H2O and CO2 ices created from the spectral fitting, we show a significant difference in the spatial distribution between H2O and CO2 ices on a galactic scale; CO2 ice is more concentrated near the galactic center. We find a strong negative correlation between the CO2/H2O ice abundance ratios and the PAH 3.3 μm/Brα ratios, indicating that the CO2/H2O ice abundance ratios are high in H II-dominated regions, while they are small in PDR-dominated regions. The result suggests that massive stars are important to enhance the CO2/H2O ice abundance ratios. Increase of cosmic-ray induced UV photons due to the intensive starburst activities may cause the high CO2/H2O ice abundance ratios in the galactic center.

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