Exploring the Ice-Forming Interstellar Environment in Nearby Galaxies with *SPICA*

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ABSTRACT

Absorption features due to interstellar ices are important probes of the interstellar environment. However ices in nearby galaxies have not been fully studied yet. With the *AKARI* near-infrared spectroscopy, we systematically observed 120 nearby galaxies, and detected H_2O ice at 3.05 μm from 36 galaxies and CO_2 ice at 4.27 μm from 9 galaxies. We find that ices are formed in the dust-rich and star-forming environment, and that CO_2 ice may be efficiently formed due to massive star formation activities. With *SPICA*, we propose spectral mapping observations of ices for the *AKARI* sample galaxies. Based on the results, we will reveal spatial variations of the ice-forming interstellar environments within galaxies in detail.

1. INTRODUCTION

Absorption features due to interstellar ices are observed in near- and mid-infrared spectra (e.g, H_2O ice at 3.05 μm and CO_2 ice at 4.27 μm). Ices are formed on the surface of dust grains in dense molecular clouds. The ice features are thought to be useful probes of the interstellar environment such as temperature, chemistry, and the radiation field. In this context, CO_2 ice is an important one since it is a secondary product unlike H_2O ice which is primarily formed on dust grains via surface reactions (Oba et al. 2012). The possible formation process is $H_2O + CO + h\nu \rightarrow CO_2 + 2H$, where $h\nu$ indicates far-UV photons (Watanabe & Kouchi 2002). Therefore, the abundance of CO_2 relative to H_2O ice may have information on the UV radiation field. However, only a handful of observations were performed for CO_2 ice especially in nearby galaxies due to the atmospheric absorption. In this study, we systematically observed H_2O and CO_2 ices in nearby galaxies with *AKARI*. Based on the results, we construct the sample of galaxies where ices are detected, and explore the ice-forming interstellar environment.

2. OBSERVATION

We used the grism slit spectroscopic mode of the *AKARI*/IRC to obtain near-infrared spectra between 2.5 and 5 μm, which have the spectral resolution of $R \sim 100$. We analyzed the spectra of 211 regions in 120 galaxies which are observed in the framework of the *AKARI* mission program ISMGN (Kaneda et al. 2009) during 2006–2010. For example, our

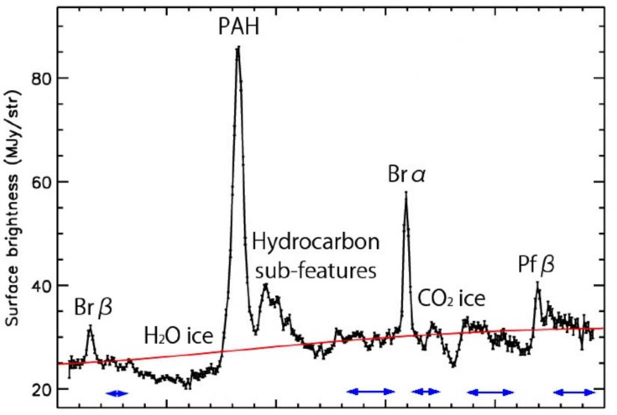

Figure 1. Example of the observed spectra for NGC 3256. The red curve and blue arrows represent the best-fit continuum model and the spectral ranges used to fit the continuum model, respectively.

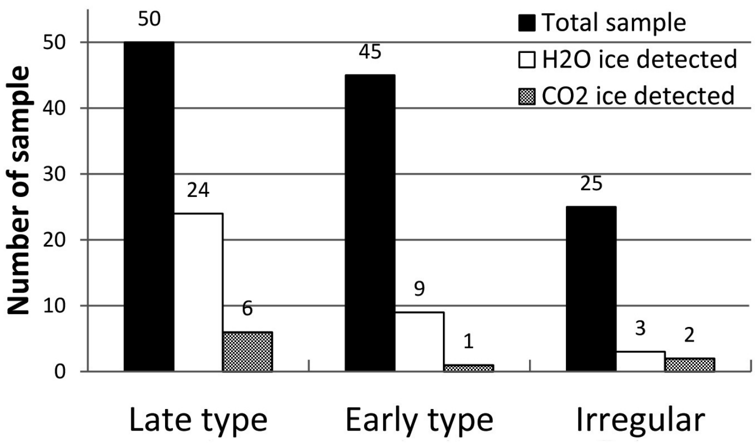

Figure 2. Numbers of the galaxies where H_2O and CO_2 ices are detected, classified in the three morphological types.

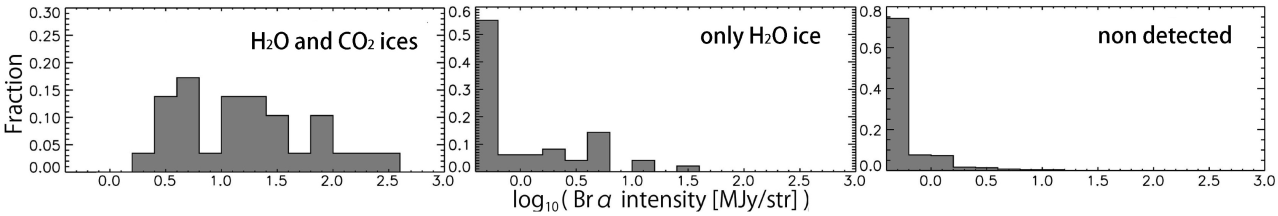

Figure 3. Fractional numbers of the galaxies with H_2O and CO_2 ices detected, with only H_2O ice detected, and without ice detection as a function of the Brα intensity.

sample includes the following famous nearby galaxies; M 31, NGC 253, NGC 6946, M 101, M 51, NGC 2768, Centaurus A (Cen A), IC 10, and NGC 205.

3. RESULTS AND DISCUSSION

Figure 1 shows an example of the observed spectra, which shows absorption features due to H_2O and CO_2 ices as well as several emission features. We search for the absorption features due to the ices based on the following method. First, we fit a continuum spectrum by a multi-temperature (200, 400, 800, 1600, and 3200 K) blackbody model. Then we obtain an optical depth spectrum and fit it by the model spectra of H_2O and CO_2 ices. We derive the column density, N, from the equation $N = \int \tau d\nu / A$, where A, τ , and ν are the band strength of each ice feature (Gerakines et al. 1995), an optical depth, and a wavenumber, respectively. As a result, we detect H_2O ice from 36 galaxies ($> 3\sigma$) and CO_2 ice from 9 galaxies ($> 2\sigma$) out of 120 galaxies.

Figure 2 shows the numbers of the galaxies where the H_2O and CO_2 ices are detected, classified in the three morphological types: late type, early type, and irregular. As can be seen in the figure, the ices are detected in late type galaxies with a high rate, while the detection is relatively rare in early type and irregular galaxies. As a global trend, late type galaxies show active star formation activities with abundant dust and gas, while early type galaxies do not. Therefore the ices may be present in the active and dust/gas-rich environment.

Next, we examine the role of star formation activities in the formation of the ices. Figure 3 shows the fractional numbers of the regions with the H_2O and CO_2 ices detected, with only the H_2O ice detected, and without ice detection as a function of the Brα intensity. These histograms clearly show that the regions with the CO_2 ice show higher Brα intensities than the others. Thus star formation activities may be essential to form the CO_2 ice, which supports the formation process of the CO_2 ice described in Watanabe & Kouchi (2002).

Finally, we examine the relation between the abundance of the CO_2 ice and star formation activities with the spatial information. Figures 4(a) and 4(b) show the maps of the column densities of the H_2O and CO_2 ices for the starburst galaxy M 82 (Yamagishi et al. 2013). In the figures, there is a clear difference in the spatial distributions of the ices; H_2O ice is widely distributed, while CO_2 ice is concentrated near the galactic center. This result suggests the difference in the UV radiation field in the galactic center and other regions. Figure 4(c) shows the CO_2/H_2O abundance ratios plotted against the PAH 3.3 μm/Brα ratios, in which there is a clear negative correlation. We furthermore find that CO_2/H_2O abundance ratios are high in the galactic center. The PAH 3.3 μm/Brα ratio represents the softness of the UV radiation field which depends on the number of massive stars. Thus massive star formation activities in the galactic center may cause the high CO_2/H_2O abundance ratios. Here it is notable that interstellar UV photons cannot penetrate into dense molecular clouds. A possible origin of the UV photons is the interactions between cosmic-rays and molecular hydrogen

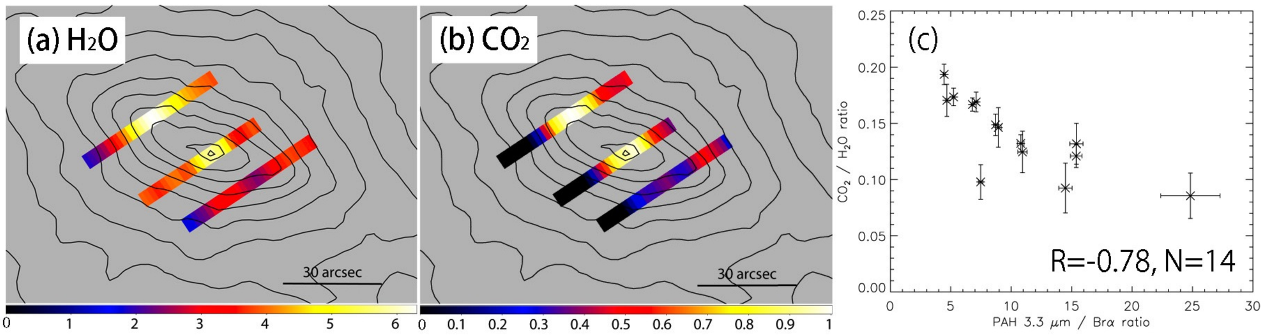

Figure 4. Column density maps of (a) H_2O and (b) CO_2 ices in M 82 in units of 10^{17} cm^{-2}. (c) The CO_2/H_2O abundance ratios plotted against the PAH 3.3 μm/Brα ratios. The contours in (a) and (b) are taken from the *AKARI* 7 μm image.

which produce far-UV photons (Prasad & Tarafdar 1983). Many supernova remnants due to the starburst activities may increase the cosmic-ray energy density in the galactic center.

4. PROSPECTS FOR *SPICA*

In order to expand the study of the interstellar ices with *AKARI*, we propose spectral mapping observations of the *AKARI* sample galaxies with high spatial resolution. The study in M 82 indicates that spatial information is critical to discuss the relation between the abundance of the ices and the interstellar environment. Hence with *SPICA*, we will observe H_2O ice at 6 and 13 μm, CO_2 ice at 15 μm and several emission features in the mid- and far-infrared. We establish reliable tracers of massive star formation activity in the mid- or far-infrared (e.g, PAH 11.3 μm/[Ne II], PAH 17 μm/[Si II], and [C II]/[O III]) as we used the PAH 3.3 μm/Brα ratio in the near-infrared. Comparing the spatial distributions of the ices with those of the tracers, we will reveal spatial variations of the ice-forming interstellar environments within the galaxies in detail.

5. SUMMARY

We systematically observed 120 galaxies with *AKARI* near-infrared spectroscopy, and detected H_2O ice from 36 galaxies and CO_2 ice from 9 galaxies. We find that the ices are detected in the star-forming and dust/gas-rich galaxies, and furthermore that CO_2 ice is formed in regions which show massive star formation activities. In M 82, CO_2 ice is abundant relative to H_2O ice in the galactic center, which may be caused by the massive star formation activities. Increase of cosmic-ray induced UV photons due to the starburst activities may cause the high CO_2/H_2O ice abundance ratios. Spectral mapping with *SPICA* is crucial to expand our study of the interstellar ices, and explore the spatial variation of the ice-forming interstellar environment within a galaxy in detail.

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