AKARI NEAR-INFRARED SPECTROSCOPIC OBSERVATIONS OF INTERSTELLAR ICES IN THE EDGE-ON STARBURST GALAXY NGC 253

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ABSTRACT

We present the spatially resolved near-infrared (2.5–5.0 µm) spectra of the edge-on starburst galaxy NGC 253 obtained with the Infrared Camera on board AKARI. Near the center of the galaxy, we clearly detect the absorption features of interstellar ices (H2O: 3.05 µm, CO2: 4.27 µm, and XCN: 4.62 µm) and the emission of polycyclic aromatic hydrocarbons (PAHs) at 3.29 µm and hydrogen recombination line Brα at 4.05 µm. We find that the distributions of the ices differ from those of the PAH and gas. We calculate the column densities of the ices and derive the abundance ratios of (CO2)/H2O = 0.17 ± 0.05. They are similar to those obtained around the massive young stellar objects in our Galaxy (0.17 ± 0.03), although a much stronger interstellar radiation field and higher dust temperature are expected near the center of NGC 253.

Key words: galaxies: individual (NGC 253) – galaxies: ISM – infrared: galaxies – ISM: abundances – ISM: molecules

1. INTRODUCTION

The 2.5–5.0 µm near-infrared (NIR) spectra of the interstellar media (ISMs) in galaxies are dominated by various emission and absorption features. For example, the absorption of various ice species (solid-state molecules, e.g., H2O: 3.05 µm, CO2: 4.27 µm, XCN: 4.62 µm, and CO: 4.67 µm), as well as the emission of polycyclic aromatic hydrocarbons (PAHs) at 3.29 µm and hydrogen recombination lines such as Brα at 4.05 µm, is included in the NIR regime. In particular, ices are important to understand interstellar chemistry, since the absorption profiles of ices are known to be sensitive to the chemical composition and the temperature of dust grains (e.g., Pontoppidan et al. 2008; Zasowski et al. 2009).

Ices around young stellar objects (YSOs) in our Galaxy and the Large Magellanic Cloud (LMC) have been studied well until now (e.g., Gerakines et al. 1999; Gibb et al. 2004; Oliveira et al. 2011; Seale et al. 2011). Shimonishi et al. (2008, 2010) showed that the abundance ratios N(CO2)/N(H2O) around massive YSOs in the LMC (0.36 ± 0.09) are significantly higher than those in our Galaxy (0.17 ± 0.03; Gerakines et al. 1999; Gibb et al. 2004). Ices are also detected in Galactic quiescent molecular clouds; Whittet et al. (2007) reported that they show the abundance ratios of 0.18 ± 0.04. Ices in nearby galaxies, however, have not been studied well; there are only a few reports about the detection of ices. Sturm et al. (2000) reported the first detection of H2O ice absorption in the NIR and mid-infrared spectra of NGC 253 and M 82 with the Infrared Space Observatory (ISO) Short Wavelength Spectrometer. Following the detection of the H2O ice, the detection of the CO2, XCN, and CO ices was reported in the nucleus of NGC 4945 (Spoon et al. 2000, 2003). However, a spatially resolved study about ices has not yet been conducted except for the L- and M-band study of the circumnuclear 10′′ region of NGC 4945 by Spoon et al. (2003).

NGC 253 is a well-studied starburst galaxy at a distance of 3.5 Mpc (Rekola et al. 2005), which has a large inclination angle (~80°). Due to the high inclination angle, we can gain high column densities along the line of sight. Hence, it is relatively easy to detect various absorption features, if there are any, from NGC 253. The kinematic center of NGC 253 is a compact radio source at a wavelength of 2 cm, TH2, while the peak of NIR emission is spatially separated from the TH2 by 4″ (see Figure 1). The NIR peak is thought to be a young superstar cluster (Keto et al. 1999; Kornei & McCrady 2009). In Figure 1, prominent dust lanes are visible on the north and the southwest side of the NIR peak. Kuno et al. (2007) presented the integrated 12CO map of NGC 253 with the beam size of 15″. In the CO map (Figure 1), there is no apparent structure corresponding to the NIR dust lane. The central activity of the galaxy is known to be strong enough to produce prominent X-ray (Dahlem et al. 1998) and Hα (Hoopes et al. 1996) as well as large-scale H1 plumes (Boomsma et al. 2005). Moreover, AKARI clearly detected far-infrared dust outflow from the galactic disk (Kaneda et al. 2009b). Tacconi-Garman et al. (2005) showed the distribution of PAH 3.3 µm emission for the central region of NGC 253 by using the narrowband images with the Very Large Telescope.

In this Letter, we present the NIR (2.5–5.0 µm) spectra of NGC 253 obtained with the Infrared Camera (IRC; Onaka et al. 2007) on board the AKARI satellite (Murakami et al. 2007). The spectra clearly show the absorption features of the H2O and CO2 ices. Based upon the spectra, we discuss the interstellar chemical condition in NGC 253.

2. OBSERVATIONS AND DATA REDUCTION

The NIR spectroscopic observations were performed as part of the AKARI mission program “ISM in our Galaxy and Nearby galaxies” (ISMGN; Kaneda et al. 2009a) in the AKARI post-helium phase (phase 3). The observations were carried out on 2009 December 21. To obtain 2.5–5.0 µm spectra, we used a grism spectroscopic mode (R ~ 120) with the slit of 5″ × 48″ for its width and length, respectively (Ohyama et al. 2007). Figure 1 shows the slit positions of the observations and the regions from which we created the spectra. We observed two
regions in NGC 253, the north and south sides of the NIR peak (ObsIDs 1422187 and 1422196). To avoid saturation effects, each region was selected not to cover the NIR peak. We observed each region two times to improve data quality.

The basic spectral analysis was performed by using the standard IDL pipeline prepared for reducing phase 3 data with a newly calibrated spectral response curve.\(^4\) In addition to the basic pipeline process, we applied the following custom procedures to improve signal-to-noise ratios for each spectrum: Before creating a spectrum, we removed hot pixels from the two array images, where pixel intensities are replaced by the median values of contiguous 8 pixels, and then we obtained two spectra for the same region by integrating pixel intensities over the spatial scale of 7.5′ along the direction of the slit length. Next, we combined the two spectra by calculating a median value of 6 pixels, where 3 pixels in the direction of wavelength per spectrum were considered for the calculation. Standard deviations were then adopted as flux errors. Finally, we applied smoothing with a boxcar kernel of 3 pixels (∼0.03 μm) in the direction of wavelength. We neglected the background of each spectrum since signals in a region 5′ away from the center of NGC 253 are about a hundred times smaller than those of the center.

3. RESULT

The obtained spectra are shown in Figure 2. The surface brightness of the spectra is different from region to region; the S1 and N1 spectra show the highest surface brightness for each slit aperture, which monotonically decreases toward the N5 and S5 spectra. The slopes of the spectra also change from the N1 and S1 to the N5 and S5 spectra. Several strong features are detected in the spectra: PAH emission at 3.3 μm, hydrogen recombination line Brα at 4.05 μm, and the absorption of ices. The absorption features of the H2O ice centered at 3.05 μm and the CO2 ice at 4.27 μm are detected in all the spectra. Some spectra also show the absorption feature of XCN ice at 4.62 μm and the pure rotational line of molecular hydrogen H2S(9) at 4.69 μm. With ISO, Sturm et al. (2000) reported only the detection of the H2O ice, and hence this is the first detection of the CO2 and XCN ices in NGC 253. The PAH emission at 3.3 μm is also detected in all the spectra. The spatial distribution of the PAH 3.3 μm emission to the southwest direction from the NIR peak is at least 2.5 times wider than that shown in Tacconi-Garman et al. (2005) owing to high sensitivity in the space observations.

To obtain continuum spectra, we fit the continuum regions at 2.65–2.70 μm, 3.60–3.70 μm, 4.10–4.15 μm, 4.35–4.45 μm, and 4.85–4.95 μm by a fourth-order polynomial. The best-fit continuum curve for each spectrum is shown in Figure 2. We divide the original spectra by the continuum spectra to derive the optical depth spectra (Figure 3).

To calculate the column densities of the H2O ice, we fit a Gaussian profile to the optical depth spectra (Figure 3). Since the present spectra resolve the absorption feature of the H2O ice, we can measure a true optical depth. However, we have to

\(^4\) http://www.ir.isas.jaxa.jp/ASTRO-F/Observation/
consider the contribution of the PAH emission at 3.3 \( \mu m \) and its sub-features at 3.4 and 3.5 \( \mu m \) to the absorption of the H\(_2\)O ice. Hence, Lorentzian profiles are included in the model fitting for the 3.3 and 3.4 \( \mu m \) features and a Gaussian for the 3.5 \( \mu m \) feature to fit the range of 2.65–3.65 \( \mu m \). We first fitted the S1 spectrum, determined the widths of the Gaussian and Lorentzian profiles, and then applied the same widths to the other spectra. In the spectral fitting, the centers of Gaussian and Lorentzian profiles are fixed at 3.05, 3.29, 3.42, and 3.50 \( \mu m \) for the H\(_2\)O ice, 3.3, 3.4, and 3.5 \( \mu m \) features, respectively. The result of fitting to one of the optical depth spectra is shown in Figure 3.

The derived optical depths of the H\(_2\)O ice in the N1 and S1 regions (\( \tau = 0.23 \pm 0.2 \) for both regions) are consistent with that previously measured by ISO (\( \tau \sim 0.25 \); Sturm et al. 2000) within the errors; the S1, S2, N1, and N2 regions overlap with the slit aperture of Sturm et al. (2000). We derive the column density, \( N \), from the equation

\[
N = \int \tau dv/A,
\]

where \( A \), \( \tau \), and \( v \) are the band strength of each ice feature measured in a laboratory, an optical depth, and a wavenumber, respectively. The band strength of 2.0 \( \times 10^{18} \) cm molecule\(^{-1} \) is used for the H\(_2\)O ice (Gerakines et al. 1995).

On the other hand, the present spectra cannot resolve the absorption feature of the CO\(_2\) ice. We, however, applied the method of integrating the optical depth spectra rather than a curve-of-growth method since the equivalent width of CO\(_2\) ice absorption is very small (\( \sim 0.01 \) \( \mu m \)). Hence, we use a Gaussian profile to fit each optical depth spectrum of the CO\(_2\) ice and used the fitting range of 4.20–4.35 \( \mu m \) in the above equation, we use the band strength of 7.6 \( \times 10^{17} \) cm molecule\(^{-1} \) (Gerakines et al. 1995). The systematic error of each column density is estimated to be 15% for the H\(_2\)O ice and 10% for the CO\(_2\) ice. The errors are evaluated by changing the above-defined continuum regions with small shifts of \( \pm 0.05 \) \( \mu m \) for both ices.

The derived column densities of the H\(_2\)O and CO\(_2\) ice, the integrated line intensities of PAH 3.3 \( \mu m \), Br\( \alpha \), and H\(_2\)S(9), and the surface brightness at 2.7 \( \mu m \) and 4.9 \( \mu m \) are shown in Figure 3. The surface brightness at 2.7 \( \mu m \) and 4.9 \( \mu m \) is the median values over the wavelength ranges of 2.65–2.75 \( \mu m \) and 4.85–4.95 \( \mu m \), respectively. In Figure 3, the spatial profiles of the ices are different from the other features; the integrated line intensity and the surface brightness have peaks at the N1 and S1 regions and decrease rapidly to the N5 and S5 regions except the integrated intensity of the H\(_2\)S(9), while the column densities of the ices show much smaller changes from region to region. In addition, on the south side, the ices show peaks in the S3 and S4 regions far from the NIR peak. These profiles suggest that the absorbers responsible for the ice features are more widely distributed than the line and the continuum emitters. The profiles of the H\(_2\)O and CO\(_2\) ices are similar to each other, suggesting a good correlation between the column densities of the H\(_2\)O and CO\(_2\) ice, although the phase of the gas dominating the spectral features differs from region to region.

The N1 and N2 spectra show weaker continuum emission than the S1 and S2 spectra due to the presence of the NIR dust lane on the north side of the NIR peak (Figure 1). In the S3 and S4 regions, another prominent dust lane is visible, which presumably contributes to the larger column densities of the ices. Thus, some of the ices responsible for the observed absorption are likely to be associated with the dust lanes, while the others are not. On the other hand, the distribution of the CO emission does not show clear spatial correspondence with those of the ice absorptions and the dust lanes. The CO map in Figure 1 reveals a more centrally concentrated distribution, which does not have a local maximum around the sub-apertures of S3 and S4, although the beam size of the CO map (\( \sim 15'' \)) is somewhat larger than the spatial scale of the sub-apertures (\( \sim 7'' \)). Therefore, a majority of the CO molecular clouds do not significantly contribute to the observed absorptions due to the ices.

In Figure 4, we show the correlation plot of the derived column densities of the H\(_2\)O and CO\(_2\) ices, which shows a linear correlation on both sides of the NIR peak. There is no systematic difference in the relation between the north and south regions. From the slope of the best-fit line to the data, the averaged CO\(_2\)/H\(_2\)O ice ratio is calculated to be 0.17 \( \pm 0.05 \). The ratio is similar to that obtained from the Galactic massive YSOs (0.17 \( \pm 0.03 \); Gerakines et al. 1999; Gibb et al. 2004).
In our observation, we detect the superposition of ices in various kinds of clouds present along the line of sight, while the observations of the Galactic YSOs trace the chemical environment of individual star-forming clouds. Therefore, it is interesting that these observations show similar CO2/H2O ice ratios despite the different situations.

In the above calculation, we assume the following geometry: the continuum emissions are in the background and absorbed by the ices with the covering fraction of 100% for each sub-aperture, while the PAH 3.3 μm emission and its sub-features are distributed in the foreground of the ices. We also calculate the column densities in the case that the covering fraction of the ice features is 50%. Then, the column densities change to (4.8–16.8) × 10^{17} cm^{-2} and (1.1–3.1) × 10^{17} cm^{-2} for the H2O and CO2 ice, respectively, and the CO2/H2O ice ratio of 0.17 ± 0.05, the same as above, is obtained. However, if the covering fraction is small, there is a possibility that the observed broad profile of the H2O ice feature might be saturated. We therefore compare the obtained optical depth spectra of the H2O ice with those obtained in the laboratory from the Leiden Molecular Astrophysics database (Ehrenfreund et al. 1996). We use the laboratory profile of the pure H2O ice at 10 K. As a result, we do not find any significant difference between both optical depth spectra. Therefore, it is unlikely that the observed profiles of the H2O ice are saturated. Moreover, we also calculate the column densities of the H2O ice in the case that the PAH 3.3 μm emission and its sub-features are distributed in the background of the ices. Then, we derive the slightly (∼2%) smaller column densities of the H2O ice than the above calculation. Thus, our results do not significantly depend on the assumed geometry.

On the other hand, Shimonishi et al. (2008, 2010) showed that the CO2/H2O ice abundance ratios of the massive YSOs in the LMC (0.36 ± 0.9) are significantly higher than those in our Galaxy. Shimonishi et al. (2008, 2010) interpreted that the high ratio is caused by the relative increase of the CO2 ice possibly due to either strong interstellar ultraviolet (UV) photon irradiation to H2O–CO binary ice mixtures (e.g., Watanabe et al. 2007) or relatively high dust temperatures (Bergin et al. 1999; Ruffle & Herbst 2001).

In the center of NGC 253, nuclear starburst has occurred (Dudley & Wynn-Williams 1999), which indicates the existence of strong UV radiation field. The detection of XCN ice at 4.62 μm is indicative of strong UV irradiation (Bernstein et al. 2000; Spoon et al. 2003). The slopes of the NIR continuum spectra suggest the presence of hot dust. Therefore, our result suggests that intense interstellar UV radiation field and high dust temperatures are not important factors to determine the ice abundance ratio. Metallicity in NGC 253 is known to be close to a solar value, Z ∼ 1 Z⊙ (Webster & Smith 1983), while Z ∼ 0.3 Z⊙ for the LMC (Luck et al. 1998). Therefore, the interstellar metallicity might be an important chemical condition to affect the ice abundance ratio.

4. CONCLUSIONS

With AKARI, we have performed the NIR (2.5–5.0 μm) spectroscopic observation of the central region of the edge-on starburst galaxy NGC 253. We clearly detect the absorption features of the H2O, CO2, and XCN ices in addition to the PAH 3.3 μm feature and its sub-features at 3.4–3.5 μm, the hydrogen recombination line Brα at 4.05 μm, the molecular hydrogen pure-rotational line H2S(9) at 4.69 μm, and hot dust continuum emission. We, for the first time, obtain the spatial variations of the ice absorption features for nearby galaxies. We find that the ices have different distributions from PAH, ionized gas, molecular gas, and hot dust. We evaluate the column densities of the H2O and CO2 ices and derive their abundance ratios, N(CO2)/N(H2O), of 0.17 ± 0.05. The obtained ratios are very close to those observed for massive YSOs in our Galaxy. However, they are significantly lower than those in the LMC where strong UV radiation and high dust temperatures are expected but not as much as in the central region of NGC 253. Therefore, we conclude that an intense interstellar UV radiation...
field and high dust temperatures are not important factors to determine the ice abundance ratio.

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REFERENCES

Bergin, E. A., Neufeld, D. A., & Melnick, G. J. 1999, ApJ, 510, L145
Bernstein, M. P., Sandford, S. A., & Allamandola, L. J. 2000, ApJ, 542, 894
Boomsma, R., Oosterloo, T. A., Fraternali, F., van der Hulst, J. M., & Sancisi, R. 2005, A&A, 431, 65
Dahlem, M., Weaver, K. A., & Heckman, T. M. 1998, ApJS, 118, 401
Gerakines, P. A., & Wynn-Williams, C. G. 1999, MNRAS, 304, 549
Ehrenfreund, P., Boogert, A. C. A., Gerakines, P. A., Jansen, D. J., Schutte, W. A., Tielens, A. G. G. M., & van Dishoeck, E. F. 1996, A&A, 315, L341
Gerakines, P. A., Schutte, W. A., Greenberg, J. M., & van Dishoeck, E. F. 1995, A&A, 296, 810
Gibb, E. L., Whittet, D. C. B., Boogert, A. C. A., & Tielens, A. G. G. M. 2004, ApJS, 151, 35
Hoopes, C. G., Walterbos, R. A. M., & Greenwell, B. E. 1996, AJ, 112, 1429
Kaneda, H., Koo, B. C., Onaka, T., & Takahashi, H. 2009a, Adv. Space Res., 44, 1038
Kaneda, H., Yamagishi, M., Suzuki, T., & Onaka, T. 2009b, ApJ, 698, L125
Keto, E., Hora, J. L., Fazio, G. G., Hoffmann, W., & Deutsch, L. 1999, ApJ, 518, 183
Kornei, K. A., & McCrady, N. 2009, ApJ, 697, 1180
Kuno, N., et al. 2007, PASJ, 59, 117
Lucy, R. E., Moffett, T. J., Barnes, T. G., III., & Gieren, W. P. 1998, AJ, 115, 605
Murakami, H., et al. 2007, PASJ, 59, S369
Ohyama, Y., et al. 2007, PASJ, 59, S411
Oliveira, J. M., et al. 2011, MNRAS, 411, L36
Onaka, T., et al. 2007, PASJ, 59, S401
Pontoppidan, K. M., et al. 2008, ApJ, 678, 1005
Ruffle, D. P., & Herbst, E. 2001, MNRAS, 324, 1054
Seale, J. P., Looney, L. W., Chen, C.-H. R., Chu, Y.-H., & Gruendl, R. A. 2011, ApJ, 727, 36
Shimonishi, T., Onaka, T., Kato, D., Sakon, I., Ita, Y., Kawamura, A., & Kaneda, H. 2008, ApJ, 686, L99
Shimonishi, T., Onaka, T., Kato, D., Sakon, I., Ita, Y., Kawamura, A., & Kaneda, H. 2010, A&A, 514, A12
Spoon, H. W. W., Koornneef, J., Moorwood, A. F. M., Lutz, D., & Tielens, A. G. G. M. 2000, A&A, 357, 898
Spoon, H. W. W., Moorwood, A. F. M., Pontoppidan, K. M., Cami, J., Kregel, M., Lutz, D., & Tielens, A. G. G. M. 2003, A&A, 402, 499
Sturm, E., Lutz, D., Tran, D., Feuchtgruber, H., Genzel, R., Kunze, D., Moorwood, A. F. M., & Thornley, M. D. 2000, A&A, 358, 481
Tacconi-Garman, L. E., Sturm, E., Lehnert, M., Lutz, D., Davies, R. I., & Moorwood, A. F. M. 2005, A&A, 432, 91
Watanabe, N., Mouri, O., Nagaoka, A., Chigai, T., Kouchi, A., & Pirronello, V. 2007, ApJ, 668, 1001
Webster, B. L., & Smith, M. G. 1983, MNRAS, 204, 743
Whittet, D. C. B., Shenoy, S. S., Bergin, E. A., Chiar, J. E., Gerakines, P. A., Gibb, E. L., Melnick, G. J., & Neufeld, D. A. 2007, ApJ, 655, 332
Zasowski, G., Kemper, F., Watson, D. M., Furlan, E., Bohac, C. J., Hull, C., & Green, J. D. 2009, ApJ, 694, 459