AKARI NEAR-INFRARED SPECTROSCOPY: DETECTION OF \textit{H}_2\textit{O} AND \textit{CO}_2 ICES TOWARD YOUNG STELLAR OBJECTS IN THE LARGE MAGELLANIC CLOUD

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ABSTRACT

We present the first results of \textit{AKARI} Infrared Camera near-infrared spectroscopic survey of the Large Magellanic Cloud (LMC). We detected absorption features of the \textit{H}_2\textit{O} ice 3.05 \textmu m and the \textit{CO}_2 ice 4.27 \textmu m stretching mode toward seven massive young stellar objects (YSOs). These samples are for the first time spectroscopically confirmed to be YSOs. We used a curve-of-growth method to evaluate the column densities of the ices and derived the \textit{CO}_2/\textit{H}_2\textit{O} ratio to be 0.45 ± 0.17. This is clearly higher than that seen in Galactic massive YSOs (0.17 ± 0.03). We suggest that the strong ultraviolet radiation field and/or the high dust temperature in the LMC may be responsible for the observed high \textit{CO}_2 ice abundance.

Subject headings: circumstellar matter — dust, extinction — ISM: abundances — ISM: molecules — Magellanic Clouds — stars: pre–main-sequence

1. INTRODUCTION

Properties of extragalactic young stellar objects (YSOs) provide us important information on the understanding of the diversity of YSOs in different galactic environments. The Large Magellanic Cloud (LMC), the nearest irregular galaxy to our Galaxy (≈50 kpc; Alves 2004), offers an ideal environment for this study since it holds a unique metal-poor environment (Luck et al. 1998). Because of its proximity and nearly face-on geometry, various types of surveys have been performed toward the LMC (e.g., Zaritsky et al. 2004; Meixner et al. 2006; Kato et al. 2007 and references therein).

An infrared spectrum of YSOs shows absorption features of heavy elements and complex molecules in a cold environment such as a dense molecular cloud or an envelope of a YSO (e.g., Chiar et al. 1998; Nummelin et al. 2001; Whittet et al. 2007; Boogert et al. 2008). These ices are thought to be taken into planets and comets as a result of subsequent planetary formation activity (Ehrenfreund & Schutte 2000). Studying the compositions of ices as functions of physical environments is crucial to understand the chemical evolution in circumstellar environments of YSOs and is a key topic of astrophysics. \textit{H}_2\textit{O} and \textit{CO}_2 ices are ubiquitous and are major components of interstellar ices (van Dishoeck & Blake 1998; Boogert & Ehrenfreund 2004). Since the absorption profile of the ices is sensitive to a chemical composition of icy grain mantles and a thermal history of local environments, the ices are important tracers to investigate the properties of YSOs. However, our knowledge about the ices around extragalactic YSOs is limited because few observations have been performed toward extragalactic YSOs. Therefore infrared spectroscopic observations toward YSOs in the LMC are important if we are to improve our understanding of the influence of galactic environments on the properties of YSOs and ices.

\textit{AKARI} is the first Japanese satellite dedicated to an infrared astronomy launched in 2006 February (Murakami et al. 2007). We have performed a near-infrared spectroscopic survey of the LMC using a powerful spectroscopic survey capability of \textit{AKARI} (IRC; Onaka et al. 2007) on board \textit{AKARI}. In this Letter, we present 2.5–5 \textmu m spectra of newly confirmed YSOs in the LMC with our survey, and discuss the abundance of \textit{H}_2\textit{O} and \textit{CO}_2 ice.

2. OBSERVATIONS AND DATA REDUCTION

The observations reported here were obtained as a part of the \textit{AKARI} IRC survey of the LMC (Ita et al. 2008). An unbiased slitless prism spectroscopic survey of the LMC has been performed since 2006 May. In this survey, the IRC02b \textit{AKARI} astronomical observing template (AOT) with the NP spectroscopy mode was used to obtain low-resolution spectra (R ~ 20) between 2.5 and 5 \textmu m. By 2008 June, 621 pointing observations were performed toward the LMC, and about 10 deg² area was observed. The near-infrared (NIR) spectroscopic survey is continuing even after the exhaustion of the liquid helium in 2008 August.

The spectral analysis was performed using the standard IDL package prepared for the reduction of \textit{AKARI} IRC spectra (Ohyama et al. 2007). Raw data were converted to dark-subtracted, linearity-corrected, and flat-field-corrected frames. Three pixels were integrated in the spatial direction to extract a point-source spectrum from the slitless spectroscopic image. Background levels of each source were estimated from the signal counts of the adjacent regions on both sides of the target spectrum. The wavelength calibration accuracy is estimated to be about ±0.01 \textmu m (Ohyama et al. 2007)

3. THE SELECTION OF YSOs

We select infrared-bright objects from the point-source catalog of the \textit{Spitzer} SAGE project (Meixner et al. 2006) with the following selection criteria: (1) [3.6] – [4.5] > 0.3 and [5.8] – [8.0] > 0.6, and (2) [3.6] < 12 and [4.5] < 11.5, where [wavelength] represents the photometric value in magnitude at each wavelength in microns. Criterion 1 refers to the YSO...
model of Whitney et al. (2004) and criterion 2 comes from the detection limit of the AKARI IRC NP mode. This rough selection is applied to the sources located in the survey area of AKARI IRC, and about 300 sources are selected. These photometrically selected sources include not only massive YSOs, but also a large number of dusty evolved stars since their infrared spectral energy distributions (SEDs) are similar to each other. For the accurate selection of YSOs, we select the sources that show absorption features of the 3.05 μm H₂O ice and the 4.27 μm CO₂ ice stretching mode in their NIR spectra taken by the present spectroscopic survey. The presence of CO₂ ice is strong evidence of YSOs since the detection of CO₂ ices toward dusty evolved stars has not been reported (Barlow 1999; Sylvester et al. 1999). Spectral overlapping with other sources located in a dispersion direction is a serious problem for slitless spectroscopy, which makes it difficult to obtain reliable spectra. We check the overlapping contamination by visual inspection, and we only use the sources without such contamination in the following analysis.

As a result, we spectroscopically confirmed seven massive YSOs in the LMC for the first time. The sources are listed in Table 1 with the observation parameters. Six of the seven sources are included in the recent YSO candidates catalog (Whitney et al. 2008), and one source (ST6) is a newly found YSO. The spectra of these sources are shown in Figure 1 together with the results of spectral fitting (see §4 for details). The absorption features of H₂O and CO₂ ices are rather broadened due to the low spectral resolution of the AKARI IRC NP spectroscopy mode but clearly detected. This is the first clear detection of the 4.27 μm stretching mode of CO₂ ice toward extragalactic YSOs. In addition, unresolved emission of PAHs and the hydrogen recombination line Pβ around 3.3 μm, the Brγ line at 4.05 μm, and blended absorption features of 4.62 μm XCN and 4.67 μm CO ices around 4.65 μm are detected toward several sources. However, it is difficult to evaluate the column densities of XCN and CO ices accurately with the present low spectral resolution data.

4. SPECTRAL FITTING

We fit a polynomial of the second to fourth order to the continuum regions and divide the spectra by the fitted continuum (Fig. 1). The wavelength regions for the continuum are set to be 2.5–2.7 μm, 3.6–3.7 μm, 4.0–4.15 μm, and 4.9–5.0 μm (Gibb et al. 2004).

Due to the low spectral resolution of the IRC NP spectroscopy mode, direct comparison of the observed spectra with the absorption profiles of laboratory ices is difficult. However, the equivalent width of absorption does not depend on the spectral resolution of the spectrum. Therefore we used a curve-of-growth method to derive the column densities of the ices. A Gaussian profile with the fixed central wavelength is fitted to the absorption bands to derive the equivalent width (Fig. 1). The vertical axis of the plot is shown in units of the normalized flux because it is difficult to estimate the optical depth directly from the present low-resolution data. We use the laboratory absorption profiles of H₂O and CO₂ ices taken from the Leiden Molecular Astrophysics database (Ennrebäud et al. 1996) to calculate the curve of growth. The profiles of pure H₂O ice and mixture of H₂O : CO₂ (100 : 14) ice both at 10 K are used for the calculation since these compositions are typical in the interstellar ices (Nummelin et al. 2001; Gibb et al. 2004). The present spectrum cannot resolve the polar and apolar CO₂ ices, and the present analysis assumes the polar CO₂ ices only. However, contribution of the apolar ice is generally small toward YSOs (Gerakines et al. 1995, 1999). The FWHM of the absorption profiles of H₂O and CO₂ ices change by approximately 10% depending on the compositions of the ices (Gerakines et al. 1999; Gibb et al. 2004). We confirm that this range of the variation in the FWHM makes negligible effects on the derived column densities compared with the observational errors. We adopt the band strengths of H₂O and CO₂ ices to be 2.0 × 10⁻¹⁶ and 7.6 × 10⁻¹⁷ cm molecule⁻¹ (Gerakines et al. 1995), respectively. The derived column densities are listed in Table 1.

Since this study applies the curve-of-growth method to the calculation of the ice column density for the first time, we check the validity of our method. We use a few Galactic YSO spectra taken by ISO SWS whose column density of H₂O and CO₂ ices are derived in Gibb et al. (2004). These high-resolution spectra are converted to low-resolution spectra by convolving the slit function of the NP spectroscopy mode, and then we derive the column density for these converted spectra using the same method described above. The comparison of the obtained column density with the value presented in Gibb et al. (2004) shows that the differences are within 10% and 20% for the H₂O ice and the CO₂ ice, respectively. The result plotted in Figure 2 includes this uncertainty in addition to the observational error.

5. RESULTS AND DISCUSSION

The obtained column densities of H₂O and CO₂ ices are plotted in Figure 2. The error bars become larger for the larger column density due to the saturation effect of the curve of growth. A linear fit to the data points indicates that the CO₂/H₂O ice column density ratio in the LMC is 0.45 ± 0.17. The large uncertainty mainly comes from the errors in the curve-of-growth analysis. For comparison, column densities of Galactic massive YSOs taken from Gibb et al. (2004) and their

### Table 1: Observation Parameters and Column Densities of Ices

| Number | AKARI ID | Obs. ID | Obs. Date | Other Name | R.A. (J2000.0) | Decl. (J2000.0) | N(H₂O) (10¹⁶ cm⁻²) | N(CO₂) (10¹⁷ cm⁻²) |
|--------|---------|--------|----------|------------|----------------|----------------|-------------------|-------------------|
| ST1    | J053931 – 701216 | 2211375 | 2007 Apr 12 | 05393117 – 7012166 | 05 39 31.15 | -70 12 16.8 | 9.6 ± 0.9 | 6.7 ± 0.3 |
| ST2    | J052212 – 675832 | 2210229 | 2006 Nov 24 | NGC 1936 | 05 22 12.56 | -67 58 32.2 | 11.1 ± 0.4 | 3.1 ± 0.1 |
| ST3    | J052546 – 661411 | 2213132 | 2007 Jun 22 | 2210076 | 05 25 46.69 | -64 14 11.3 | 29.7 ± 4.6 | 15.5 ± 1.8 |
| ST4    | J051449 – 671221 | 2200073 | 2006 Jun 6 | IRAS 05148 – 6715 | 05 14 49.41 | -67 12 21.5 | 18.7 ± 2.3 | 8.2 ± 0.5 |
| ST5    | J053054 – 683428 | 2213061 | 2007 Mar 13 | IRAS 05311 – 6836 | 05 30 54.27 | -68 34 28.2 | 31.7 ± 4.7 | 12.4 ± 1.4 |
| ST6    | J053941 – 692916 | 2201137 | 2006 Oct 25 | J0539412 – 6929166 | 05 39 41.08 | -69 29 16.8 | 59.1 ± 3.8 | 25.6 ± 1.0 |
| ST7    | J052351 – 680712 | 2210220 | 2006 Nov 29 | J05240 – 68089 | 05 23 51.15 | -68 07 12.2 | ... | ... |

* a 2MASS ID.
* b The source is in a cluster.
large, it is clear from the present results that the CO/H$_2$O ice ratio in the LMC is higher than the typical ratios of the Galactic objects. Since the distribution range of the H$_2$O ice column density in the LMC is comparable to that of the massive Galactic YSOs, it can be concluded that the abundance of the CO$_2$ ice is higher in the LMC. The present results suggest that the different galactic environment of the LMC is responsible for the high CO$_2$ abundance.

The formation mechanism of CO$_2$ ice in circumstellar environments of YSOs is not understood; however, a number of scenarios have been proposed. Several laboratory experiments indicate that the CO$_2$ ice is efficiently produced by UV photon irradiation to H$_2$O-CO binary ice mixtures (e.g., Watanabe et al. 2007). The LMC has an order-of-magnitude stronger UV radiation field than our Galaxy due to its active massive star formation (Israel et al. 1986), which could lead to the higher CO/H$_2$O ratio in the LMC. The high CO/H$_2$O ratio toward a YSO in the LMC is also reported in van Loon et al. (2005) and they suggest that a different radiation environment in the LMC is one of the reasons for the high CO$_2$ abundance. On the other hand, the model of diffusive surface chemistry suggests that high abundance of CO$_2$ ice can be produced at relatively high dust temperatures (Bergin et al. 1999; Ruffle & Herbst 2001). Several studies have reported that the dust temperature in the LMC is generally higher than in our Galaxy based on far-infrared to submillimeter observations of diffuse emission (e.g., Aguirre et al. 2003; Sakon et al. 2006). Therefore the high dust temperature may also have an effect on the high CO$_2$ ice abundance in the LMC.

It is difficult to separate the effect of the UV radiation field and the dust temperature on the high abundance of CO$_2$ ice in the LMC by our low-resolution NIR spectra. The 4.62 $\mu$m XCN feature is known to be indicative of strong UV irradiation (Bernstein et al. 2000; Spoon et al. 2003). On the other hand, detailed profile analysis of the 3.05 $\mu$m H$_2$O ice stretching mode and the 15.2 $\mu$m CO$_2$ ice bending mode should reveal the temperature and compositions of the ices (Ehrenfreund et al. 1996; Öberg et al. 2007). Future observations of the XCN feature and the H$_2$O and CO$_2$ ice features with a sufficient wavelength resolution will be useful to investigate this problem.
6. SUMMARY

We performed a near-infrared spectroscopic survey of the LMC with AKARI IRC. We spectroscopically confirmed seven massive YSOs that show absorption features of H$_2$O and CO$_2$ ices. This is the first detection of the 4.27 $\mu$m CO$_2$ ice feature toward extragalactic YSOs. The derived ice column densities indicate that the abundance of CO$_2$ ice is clearly higher in the LMC than our Galaxy. The relatively strong UV radiation field and/or high dust temperature in the LMC may be responsible for the observed high abundance of CO$_2$ ice. Our study shows the difference in the chemical composition around extragalactic YSOs, suggesting that extragalactic YSOs hold quite different environments from Galactic ones.

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