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AKARI near-infrared spectroscopy: Detection of H_2O and CO_2 ices toward young stellar objects in the Large Magellanic Cloud

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Abstract. We present the first results of the *AKARI* Infrared Camera near-infrared spectroscopic survey of the Large Magellanic Cloud (LMC). The circumstellar material of young stellar objects (YSOs) are affected by galactic environments such as a metallicity or radiation field. Ices control the chemical balance of circumstellar environments of embedded YSOs. We detected absorption features of the H_2O ice 3.05 μm and the CO_2 ice 4.27 μm stretching mode toward seven massive YSOs in the LMC. This is the first detection of the 4.27 μm CO_2 ice feature toward extragalactic YSOs. The present 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 CO_2/H_2O 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 CO_2 ice abundance.

Keywords. circumstellar matter, stars: pre-main-sequence, ISM: molecules, galaxies: individual (LMC), Magellanic Clouds

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 a YSO shows absorption features of various ices which are thought to be an important reservoir 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. H_2O and CO_2 ices are ubiquitous and are major components of interstellar ices (Boogert & Ehrenfreund 2004). Since the absorption profile of the ices is sensitive to the chemical composition

Table 1. Observation parameters and column densities of ices.

No.	AKARI ID	Obs. Date	Other Name	RA (J2000.0)	DEC (J2000.0)	$N(H_2O)$ (10^{17} cm^{-2})	$N(CO_2)$
ST1	J053931−701216	2007 Apr 12	05393117−7012166[a]	5:39:31.15	−70:12:16.8	$9.6^{+1.9}_{-1.9}$	$6.7^{+4.8}_{-3.6}$
ST2	J052212−675832	2006 Nov 24	NGC 1936	5:22:12.56	−67:58:32.2	$11.1^{+1.6}_{-1.4}$	$3.1^{+1.7}_{-1.5}$
ST3	J052546−661411	2007 Jun 22	......[b]	5:25:46.69	−66:14:11.3	$29.7^{+4.5}_{-4.6}$	$15.5^{+13.8}_{-9.4}$
ST4	J051449−671221	2006 Jun 6	IRAS F05148−6715	5:14:49.41	−67:12:21.5	$18.7^{+2.3}_{-2.3}$	$8.2^{+4.5}_{-3.7}$
ST5	J053054−683428	2007 Mar 13	IRAS 05311−6836	5:30:54.27	−68:34:28.2	$31.7^{+4.7}_{-4.5}$	$12.4^{+9.1}_{-6.8}$
ST6	J053941−692916	2006 Oct 25	05394112−6929166[a]	5:39:41.08	−69:29:16.8	$59.1^{+38.4}_{-25.0}$	...
ST7	J052351−680712	2006 Nov 29	IRAS 05240−6809	5:23:51.15	−68:07:12.2	...	$55.3^{+40.3}_{-30.3}$

Notes: [a]2MASS ID; [b]The source is in a cluster.

of icy grain mantles and the 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 (e.g., van Loon *et al.* 2005). 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 (Shimonishi *et al.* 2008).

AKARI is the first Japanese satellite dedicated to infrared astronomy launched in February 2006 (Murakami *et al.* 2007). We have performed a near infrared spectroscopic survey of the LMC using the powerful spectroscopic survey capability of the Infrared Camera (IRC; Onaka *et al.* 2007) on board *AKARI*. In this paper, we present 2.5–5 μm spectra of newly confirmed YSOs in the LMC with our survey, and discuss the abundances of H_2O and CO_2 ice.

2. Observations and data reduction

The observations reported here were obtained as a part of the *AKARI* IRC survey of the LMC (Ita *et al.* 2008). An unbiased slit-less prism spectroscopic survey of the LMC has been performed since May 2006. In this survey, the IRC02b *AKARI* astronomical observing template (AOT) with the NP spectroscopy mode was used to obtain low-resolution spectra ($R \sim 20$) between 2.5 and 5 μm.

The spectral analysis was performed using the standard IDL package prepared for the reduction of *AKARI* IRC spectra (Ohyama *et al.* 2007). The wavelength calibration accuracy is estimated to be about ~0.01 μm (Ohyama *et al.* 2007).

3. The selection of YSOs

We select infrared-bright objects from the point-source catalog of the *Spitzer* SAGE project (Meixner *et al.* 2006) with the following selection criteria: (1) [3.6] − [4.5] > 0.3 mag and [5.8] − [8.0] > 0.6 mag, and (2) [3.6] < 12 mag and [4.5] < 11.5 mag, where [wavelength] represents the photometric value in magnitude at each wavelength in μm. The criterion (1) refers to the YSO model of Whitney *et al.* (2004), and the 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 distribution (SED) are similar to each other. For the accurate selection of YSOs, we select the sources that show absorption features of the 3.05 μm H_2O ice and the 4.27 μm CO_2 ice stretching mode in their NIR spectra taken by the present spectroscopic

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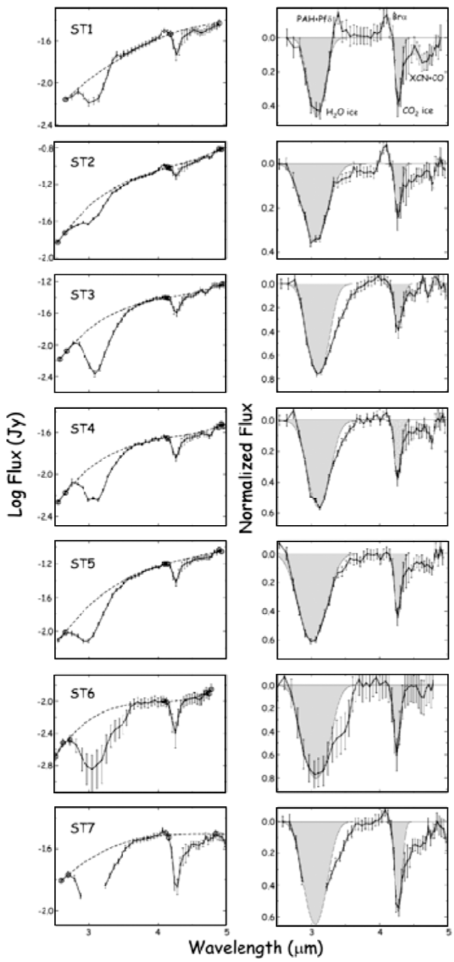

Figure 1. *AKARI* IRC 2.5–5μm spectra of YSOs in the LMC. Left: Plots of $\log_{10}$ flux(Jy) vs. wavelength(μm). Open circles represent the points used for the continuum determination. Dashed lines represent the derived continuum. Right: Plots of normalized flux ($1 - F/F_c$; F and F_c represent observed flux and continuum flux, respectively) vs. wavelength(μm). Shaded regions around 3.0 and 4.3 μm represent fitted Gaussians for the absorption features of H_2O and CO_2 ices, and the areas correspond to the equivalent widths. The positions of H_2O, CO_2, XCN, CO ice absorption bands, PAH emission bands, and hydrogen recombination lines are shown.

survey. The presence of CO_2 ice is strong evidence of YSOs since the detection of CO_2 ice toward dusty evolved stars has not been reported (Sylvester *et al.* 1999). Spectral overlapping with other sources located in the dispersion direction is a serious problem for slit-less 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 Fig. 1 together with the results of spectral fitting (see §4 for details). The absorption features of H_2O and CO_2 ices are rather broadened due to the low spectral resolution

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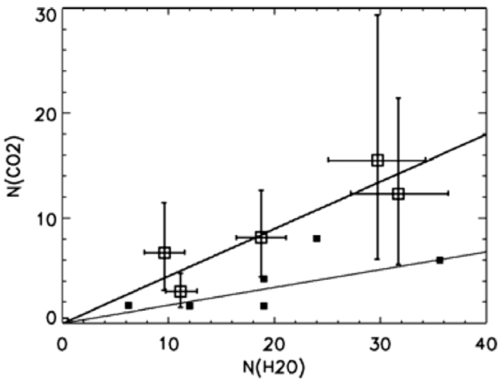

Figure 2. CO_2 ice vs. H_2O ice column density in units of 10^{17} cm^{-2}. Open squares with error bars represent the results of this study. Filled squares represent those of Galactic massive YSOs (Gibb *et al.* 2004). Upper and lower solid lines represent $CO_2/H_2O \sim 0.45$ and 0.17, respectively. The sources ST6 and ST7 are not plotted due to their large errors.

of the *AKARI* IRC NP spectroscopy mode but clearly detected. This is the first clear detection of the 4.27 μm stretching mode of CO_2 ice toward extragalactic YSOs. In addition, unresolved emission of PAHs and the hydrogen recombination line Pfδ around 3.3 μm, the Brα 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 H_2O and CO_2 ices taken from the Leiden Molecular Astrophysics database (Ehrenfreund *et al.* 1996) to calculate the curve-of-growth. The profiles of pure H_2O ice and mixture of H_2O:CO_2 (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 CO_2 ice features, and the present analysis assumes the polar CO_2 ice only. However, contribution of the apolar ice is generally small toward YSOs (Gerakines *et al.* 1995, 1999). We adopt the band strengths of H_2O and CO_2 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.

5. Results and discussion

The obtained column densities of H_2O and CO_2 ices are plotted in Fig. 2. The error bars become larger for the larger column density due to the saturation effect of the

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curve-of-growth. A linear fit to the data points indicates that the CO_2/H_2O 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 CO_2/H_2O ice column density ratio of 0.17±0.03 (Gerakines *et al.* 1999) are also plotted in Fig. 2. A similar CO_2/H_2O ratio of 0.18±0.04 is also observed toward a Galactic quiescent dark cloud (Whittet *et al.* 2007), while a relatively high CO_2/H_2O ratio of 0.32±0.02 is observed toward Galactic low- and intermediate-mass YSOs, and some of them reach ∼0.4 (Pontoppidan *et al.* 2008). Although the uncertainty is large, it is clear from the present results that the CO_2/H_2O ice ratio in the LMC is higher than the typical ratios of the Galactic objects. Since the distribution range of the H_2O 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, but a number of scenarios have been proposed. Several laboratory experiments indicate that CO_2 ice is efficiently produced by UV photon irradiation of H_2O-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 higher CO_2/H_2O ratios in the LMC. A high CO_2/H_2O ratio toward a YSO in the LMC is also reported in van Loon *et al.* (2005), who suggest that a different radiation environment in the LMC is one of the reasons for the high CO_2 abundance. On the other hand, models of diffusive surface chemistry suggests that high abundance of CO_2 ice can be produced at relatively high dust temperatures (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., Sakon *et al.* 2006). Therefore the high dust temperature may also have an effect on the high CO_2 ice abundance in the LMC.

6. Summary and future works

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_2O and CO_2 ices. This is the first detection of the 4.27 μm 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 in 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.

With our low resolution NIR spectra, 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. The 4.62 μm XCN feature is known to be indicative of strong UV irradiation (e.g., Bernstein, Sandford, & Allamandola 2000). The presence of the CO ice which has a narrow absorption feature at 4.67 μm will constrain the dust temperature due to its low sublimation temperature. Furthermore, detailed profile analysis of the 3.05 μm H_2O ice stretching mode and the 15.2 μm CO_2 ice bending mode should reveal the temperatures and compositions of the ices (Ehrenfreund *et al.* 1996; Öberg *et al.* 2007). Near- to mid-infrared future observations with sufficient wavelength resolution are necessary to investigate the properties of extragalactic YSOs.

On the other hand, we need to increase samples of extragalactic YSOs which show absorption features of ices. The present spectroscopic survey is expanding the survey area, and also is performing a survey toward the Small Magellanic Cloud. These observations are expected to increase the samples of the Magellanic Clouds' YSOs, and will contribute to the study of extragalactic YSOs.

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