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Observational study of ice around extragalactic Young Stellar Objects with *AKARI*

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Abstract. Ice around young stellar objects (YSOs) is thought to be an important reservoir of heavy elements, and they control the chemical evolution of circumstellar environments of YSOs. Properties of ice around extragalactic YSOs provide us important information on the understanding of the diversity of circumstellar materials in different galactic environments. In this paper, we present the current status of our observational study of ice around embedded YSOs in the Large Magellanic Cloud.

Keywords : astrochemistry – circumstellar matter – ISM: abundances – ISM: molecules – Magellanic Clouds – infrared: ISM

1. Introduction

Question of where molecules like water or carbon dioxide on the Earth's surface came from is one of the main topics of the current astrochemistry. One of the possible origins of these molecules is the "ice" around young stellar objects (YSOs). It is known that infrared spectra of embedded YSOs show absorption features originating from various ice species (solid state molecules, e.g., Gibb

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et al. 2004; Boogert et al. 2008). It is believed that a large amount of heavy elements and complex molecules are preserved as ice in the dense and cold regions ($n_H \geq 10^4$ cm^{-3}, T $\sim$ 10 – 20K, van Dishoeck & Blake 1998). Thus investigating the compositions of ice as a function of physical environments is crucial to understand the chemical evolution of YSOs. Ice is also of interest in terms of chemical conditions of the planetary formation since it is detected toward solar system objects such as comets and icy satellites.

Observations of ice around extragalactic YSOs are one of the challenging topics in the current ice studies. So far, infrared spectroscopic observations of extragalactic embedded YSOs are limited due to observational difficulties, and their circumstellar chemistry is poorly understood. However, it is probable that different galactic environments (e.g., metallicity, radiation field, etc.) could affect the properties of circumstellar material. Thanks to the progress of the infrared space telescopes such as *AKARI* (Murakami et al. 2007), now we are able to extend the study of ice around YSOs to extragalactic objects.

The target galaxy of the present study is the Large Magellanic Cloud (LMC), which is the nearest irregular galaxy to our Galaxy. It is known that the metallicity of LMC is lower than that of our Galaxy (Z $\sim 0.3 Z_\odot$, Luck et al. 1998). Thus ice around the LMC's YSOs will provide us important information on the understanding of the properties of circumstellar materials in the metal-poor environment. In this paper, we present the current status of our observational study of ice around extragalactic YSOs with *AKARI*.

2. Searching for extragalactic YSOs

Since infrared colours and brightness of massive embedded YSOs are similar to those of dusty evolved stars, a colour-colour selection of massive YSOs is complicated and thus the number of samples in which the presence of ice features are known is limited to few objects (van Loon et al. 2005, 2008). It is known that the abundant ice species such as H_2O and CO_2 have strong absorption features in a near-infrared (NIR) wavelength range. The presence of these ice features (especially that of CO_2 ice) can be strong evidence of embedded YSOs. We performed a NIR low resolution spectroscopic survey ($2 - 5$ μm, R $\sim$ 20) of the LMC with the Infrared Camera (IRC, Onaka et al. 2007) on board *AKARI* (see Ita et al. 2008, for details of the survey). The observations were performed as a part of *AKARI* mission programme, "*AKARI* Large Area Survey of the Large Magellanic Cloud" (PI: T. Onaka). By using the enormous number of NIR spectra of the point sources in the LMC obtained in the survey, we newly confirmed massive YSOs which show absorption features of ice (Shimonishi et al. 2008). The new samples of extragalactic YSOs which are necessary for the study of circumstellar ice are provided in our earlier study.

3. Further observations of the LMC's YSOs with *AKARI*

An accurate determination of ice column densities is crucial to discuss the variation of ice abundances between the objects. However, the uncertainties in the derived column densities from the low-resolution spectra of Shimonishi et al. (2008) are large and also the weak features of relatively minor ice species such as CH_3OH and CO are difficult to identify. We thus carried out higher spectral resolution spectroscopy toward the above YSOs and some YSO candidates with the IRC as a part of *AKARI* post-helium open time program "Ice Around Extragalactic Young Stellar Objects" (PI: T. Shimonishi) and *AKARI* Director's Time (DT) observations (Shimonishi et al. 2010). We obtained near-infrared spectra (R$\sim$80, 2.5–5 μm) of 12 embedded massive YSOs in total.

One of the observed spectra is shown in Fig. 1. The absorption features of the 3.05 μm H_2O and 4.27 μm CO_2 ice are detected toward all the observed objects. Some objects show the absorption features of 3.53 μm CH_3OH ice, 4.38 μm $^{13}CO_2$ ice, 4.62 μm XCN and the 4.67μm CO ice. In addition, hydrogen recombination lines (2.62 μm Brβ, 3.05 μm Pfϵ, 3.29μm Pfδ, 3.74 μm Pfγ, 4.05 μm Brα, 4.64 μm Pfβ) and polycyclic aromatic hydrocarbon(PAH) emission bands (3.3μm and 3.4 μm) are detected in the spectra. The detection of these emission features allows detailed discussions about the correlation between ice abundances and YSO characteristics.

3.1 Different chemical conditions of extragalactic YSOs

Information that we can obtain from ice features is a column density of each ice species along the line of sight toward an object. The derived column densities of the H_2O and CO_2 ice are plotted in Fig. 2. An average CO_2/H_2O ice column density ratio of our samples is calculated to be 0.36 ± 0.09. The present samples are massive YSOs and they should be compared to Galactic massive samples. Thus the column densities of Galactic massive YSOs ($CO_2/H_2O \sim 0.17 \pm 0.03$, Gerakines et al. 1999) are also plotted in the figure for comparison. As it can be seen from Fig. 2, the typical CO_2/H_2O ice ratio toward the LMC's massive YSOs is larger than that of Galactic massive YSOs. Laboratory experiments indicate that the CO_2 ice is efficiently produced by the UV photon irradiation to H_2O-CO ice mixtures (e.g., Watanabe et al. 2007). On the other hand, a theoretical study suggests that the sufficient abundance of the CO_2 ice can be produced at relatively high dust temperatures (Ruffle & Herbst 2001). Although the formation mechanisms of the CO_2 ice are still unclear, we suggest that the strong ultraviolet radiation field and/or the high dust temperature in the LMC are responsible for the observed high abundance of the CO_2 ice.

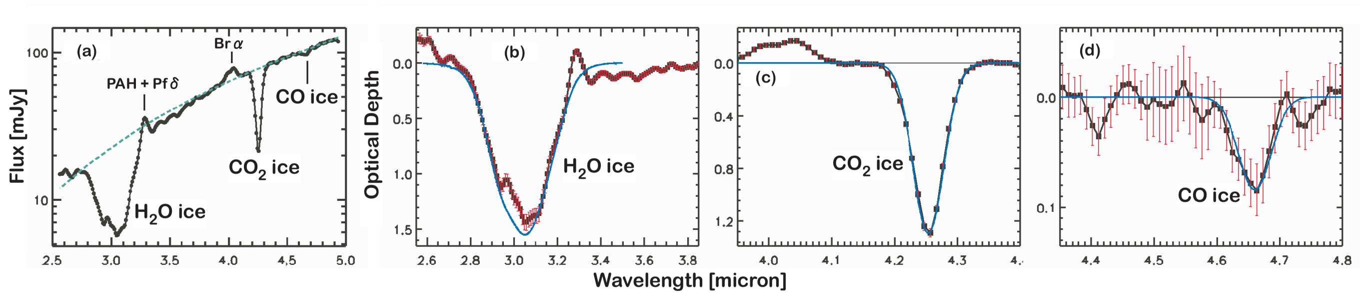

Figure 1. (a) An example of *AKARI* IRC 2.5–5μm spectra of the observed YSOs in the LMC. The positions of detected features are labeled. The dashed line represents derived continuum. (b) After the continuum subtraction. A solid line represents fitted laboratory spectra of the H_2O ice. (c), (d) A solid line represents a fitted Gaussian profile for a measurement of the equivalent width of the CO_2 and CO ice feature.

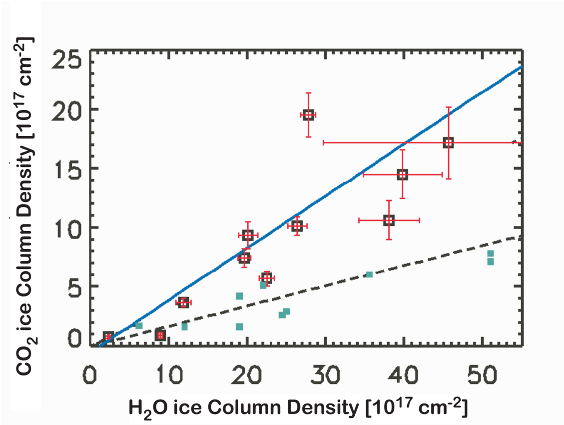

Figure 2. CO_2 ice vs. H_2O ice column density in units of 10^{17} cm^{-2}. Open squares with error bars and filled squares represent the results of this study and those of Galactic massive YSOs from Gerakines et al. (1999), respectively. An average CO_2/H_2O ice ratio of our samples (0.36) and the Galactic massive YSOs ($\sim$0.17) are plotted as solid and dashed lines. It can be seen that the CO_2/H_2O ice ratio of the LMC's YSOs is larger than that of Galactic YSOs.

Our result provides the evidence indicating that YSOs in the metal-poor galaxy hold different chemical conditions in their circumstellar environments.

3.2 Correlation between Ice Abundances and YSO Properties

The present YSO samples possess similar characteristics in their infrared SEDs, but they show a large variation in the CO_2 and CO ice abundances and their near-infrared emission features. To investigate which physical condition is dominant in the formation and evolution of ice, we here compare the derived ice abundances with the strength of the hydrogen emission line and the total luminosity, which are both a good estimate of radiation environment of individual YSOs. The equivalent width of a hydrogen emission line is measured from the observed spectra, and the total luminosity is derived by the Online SED Fitter[1] (Robitaille et al. 2007). As a result, it is shown that the CO_2 ice abundance and these YSO characteristics does not show a correlation. The present result indicates that the internal stellar radiation does not play an important role in the evolution of the CO_2 ice around a massive YSO. In contrast, it is shown that the CO ice abundance of relatively luminous and evolved samples

[1]The On-line SED Fitter is available at http://caravan.astro.wisc.edu/protostars/sedfitter.php

are much lower than other samples. We suggest that more volatile molecules like CO are susceptible to the effect of the stellar radiation.

4. Future directions

Since it is shown in the above discussions that the effect of internal stellar radiation is less dominant in the evolution of the CO_2 ice, it is worth investigating the correlation between the local environments of YSOs and their ice properties as a next step. The present YSOs are located at the various regions in the LMC. We can investigate the diversity of the ice abundance around YSOs by considering the environmental factors such as the position of YSOs in star forming regions, a population of surrounding stars, a distribution of the ISM and so on. In addition, the metallicity dependence of chemical conditions around YSOs is also an important issue. To investigate the above issues, observations of more YSO samples in the LMC, Small Magellanic Cloud (SMC) and outer region of our Galaxy with *AKARI* are now ongoing.

Also an interesting issue is ice around extragalactic low- and intermediate-mass YSOs. The present results revealed a massive YSO that shows a CO_2/H_2O ice ratio of up to $\sim$0.7. Since the interstellar ice is thought to be an origin of planetary system ice as discussed in Ehrenfreund & Schutte (2000), it will indirectly tell us the chemical diversity of subsequently-formed planets if there is a chemical difference in lower mass YSOs in the LMC.

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