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AKARI INFRARED OBSERVATIONS OF EMBEDDED YSOs IN THE MAGELLANIC CLOUDS

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ABSTRACT

Spectroscopic studies of extragalactic YSOs have shown a great progress in the last few years. Infrared observations with *AKARI* made significant contributions to that progress. In this proceeding, we are going to introduce our current research on the infrared observations of ices and dust around embedded YSOs in the Magellanic Clouds.

Key words: infrared; stars: pre-main sequence; ISM: molecules; Magellanic Clouds

1. INTRODUCTION

Chemical diversity of star-forming and planet-forming materials in the Universe is one of the great interests of present-day astronomy. Star-/planet-formation activities can occur in various kinds of galaxies which differ in size, shape, and environment. Thus it is very interesting to discuss how galactic characteristics affect the evolution of materials around YSOs. Chemical evolution of the Universe is, as a first-order approximation, the evolution of metallicity, since heavy elements are synthesized in stellar interiors by nuclear fusion reactions. From these perspectives, it is very important to investigate the properties of circumstellar materials of YSOs in various metallicity environments.

Progress in infrared observation techniques has suggested that the bulk of heavy elements in interstellar/circumstellar environments exist in the solid phase. Ices are considered to be a major reservoir of molecules such as water, carbon dioxide, and various organic compounds that are essential for the presence of life. Thus the role of ices must not be neglected in order to understand the chemical evolution of materials around a YSO. This study aims to investigate the properties of circumstellar materials under the different metallicity environment from the point of view of molecules in the ice mantle.

The LMC, SMC are the nearest irregular galaxies to our Galaxy (∼50 kpc for LMC, and ∼60 kpc for SMC, Westerlund, 1990), and they are primal observation targets for this study. There are two main reasons to study YSOs in the Magellanic Clouds. First, YSOs in the Magellanic Clouds enables us to investigate how the different metallicity environments affect the properties of circumstellar materials. This is because the LMC and SMC are low-metallicity galaxies. Their metallicities are 1/2 and 1/5 compared to the solar neighborhood (Westerlund, 1990). Next, YSOs in the Magellanic Clouds enables us to investigate the properties of circumstellar materials by comparison with the luminosity of the central star. This is because the Magellanic Clouds are sufficiently distant so that their own depth can be neglected, and thanks to their nearly face-on geometry (especially for the LMC) , we can assume that objects in the LMC and SMC are all at the same distance from us.

With the above background, we have been conducting an observational study of YSOs in the Magellanic Clouds with *AKARI* and other infrared telescopes. In this paper, we are going to introduce our recent study on infrared observations toward YSOs in the LMC and SMC.

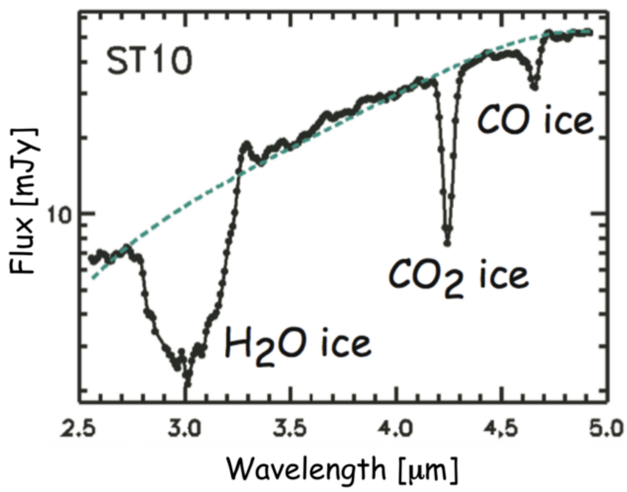

Fig. 1. Example of 2.5–5 μm spectra of LMC's YSOs obtained by the *AKARI* IRC NG spectroscopy. The dashed line represents derived continuum. The positions of detected ice features are labeled. [Figure adopted from Shimonishi et al. (2010)]

2. EMBEDDED YSO SAMPLES IN THE MAGELLANIC CLOUDS

A number of embedded YSOs are spectroscopically identified in the LMC and SMC with *AKARI*, and their near-infrared ice features are discussed in detail (Shimonishi et al., 2008, 2010, 2012). The YSOs samples and infrared data introduced in this paper is based on Shimonishi (2012, Ph.D thesis). An example of *AKARI* near-infrared spectrum of a LMC's YSO is shown in Figure 1. A large number of embedded YSOs are also reported by the *Spitzer*/IRS observations, and mid-infrared ice features are investigated in detail (Oliveira et al., 2009; Seale et al., 2011).

3. WHAT DO WE LEARN FROM MAGELLANIC YSOs?

3.1. *Infrared Luminosity vs. Ice Column Density Relation*

In order to discuss the formation and evolution of ices around YSOs, it is very useful to give information about the formation of ices in the prestellar phase. Observational evidence of the formation of ices in molecular cloud cores is clear. Observations of background stars behind a star-less molecular cloud core show the presence of major ice species in the cloud (e.g., Whittet et al., 1988). The results suggest that a sufficient amount of ices are already formed before the formation of a protostar.

Then, are ices in a molecular cloud physically or chemically processed by the formation of a protostar? If yes, then how does the protostar affect the properties of circumstellar ices? This remains a matter of debate. The radiation from the central star is presumably the dominating energy source in the envelope of a YSO. Since the stellar radiation is absorbed by circumstellar dust and re-emitted as the thermal radiation in the case of an embedded YSO, the luminosity of the central stars is measured as the total infrared luminosity. Thus it is important to investigate the dependance of ice properties on the luminosity of a YSO. Magellanic YSOs are suitable observation targets for this purpose.

Figure 2 compares the total infrared luminosities of sample YSOs and their ice column densities (H_2O ice + CO_2 ice). Ice column densities are derived from our near-infrared spectra, and luminosities are derived from the SED fitting to the infrared photometric data (see Shimonishi et al., 2010 for more details). We discovered a strong correlation between YSO's luminosities and ice column densities with a few exceptions (ST4, ST12, and ST15, labeled in the figure). The correlation coefficient except data points of ST12, and 15 is calculated to be 0.81, which can be considered as a statistically valid correlation.

A possible explanation for a decreasing ice column density with an increasing luminosity is a sublimation effect. Given a spherically-symmetric distribution of

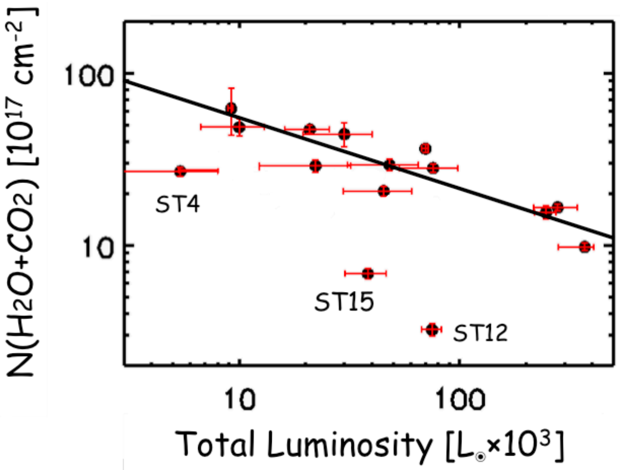

Fig. 2. Total infrared luminosity vs. H_2O + CO_2 ice column density for the LMC YSOs. A straight-line fit to the data points is represented by the solid line. A YSO number is plotted for the objects discussed in the text.

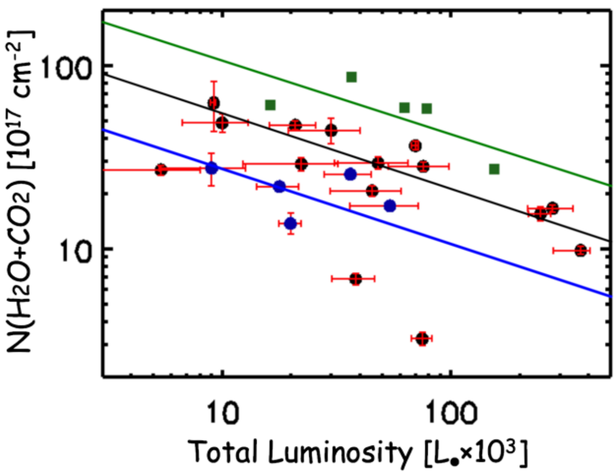

Fig. 3. Total infrared luminosity vs. H_2O + CO_2 ice column density for the LMC, SMC, and Galactic YSOs. The black and blue filled circles indicate LMC and SMC YSOs, and the green filled squares represent Galactic counterparts. The black solid line is the same as in Figure 2. The blue and green lines are results of the fitting of the LMC's line to SMC's and Galactic data points (see text for details).

dust around a central star, the increase of the stellar luminosity leads to an elevation of the dust temperature. Ices sublimate when the dust temperature exceeds the sublimation temperature of ices (typically ∼100 K for H_2O). Thus, in the envelope of a luminous YSOs, the region where the dust temperature is lower than the ice sublimation temperature is presumably smaller than in less luminous YSOs. The above result suggests that the YSO's luminosity is a key observational factor which dominates the ice processing around YSOs. The reason why the correlation between ice column densities and YSO's luminosities was not reported in current studies of Galactic samples is because it is difficult to estimate the YSO's luminosity accurately for a large number of objects in their case. We have shown that Magellanic YSOs are very useful targets to investigate the dependance of the properties of YSO's circumstellar materials on the stellar luminosity.

3.2. *Effect of Metallicity on Circumstellar Ices*

We next investigate how circumstellar ices are affected by the galactic environment by comparing YSOs in the different metallicity environments. Figure 3 shows luminosity vs. ice column density relations for LMC's, SMC's, and Galactic YSOs. We refer to Gibb et al. (2004) and Oliveira et al. (2011) for ice column densities of Galactic samples and a part of SMC samples, respectively. The linear regression line defined by using only the LMC's data points is shown. All the SMC's YSOs are distributed below this LMC line, and all the Galactic YSOs are distributed above the LMC line. It is difficult to define a similar regression line using the SMC's and Galactic YSOs because the number of data points is much smaller. Instead, we fit a line that has the same gradient but has different intercepts to the SMC's and Galactic data points.

As it is seen in the figure, YSO's ice column densities decrease from our Galaxy to the SMC, when YSOs in the same luminosity range are compared. This trend of decreasing ice column density from our Galaxy to the LMC, and to the SMC is consistent with the trend of decreasing metallicity of the parent galaxy. The value of the H_2O + CO_2 ice column density at 10^4 $L_\odot$ estimated from the regression lines is 112, 56, 30 [10^{17} cm^{-2}] for the Galactic, LMC, and SMC samples, respectively. It is very interesting that this ratio coincides with the ratio of the metallicity ([Fe/H]) of our Galaxy, LMC, and SMC (= 1 : 0.5 : 0.2). The result suggests that the amount of ices around an embedded YSO is scaled by the amount of heavy elements in the parent galaxy. This is a clear effect of galactic environment on the properties of YSO's circumstellar matters, and this is shown for the first time in this study.

In addition to the above discussions, several authors have discussed the difference in the molecular abundance of circumstellar ices between Galactic and Magellanic YSOs (Shimonishi et al., 2008, 2010; Oliveira et al., 2009). In these papers, it is reported that the abundance of the CO_2 ice is systematically higher in the LMC compared to Galactic counterparts. Although a detailed discussion is not described here due to space limitation, it can be found in the above references.

4. SPATIAL SCALE PROBED BY OBSERVATIONS OF MAGELLANIC YSOs

One of the major concerns in studies of extragalactic YSOs is the physical scale probed by observations of distant targets. The spatial resolution of the *AKARI* IRC spectroscopy presented in this paper is estimated to be approximately 5″ – 8″, which corresponds to 1.25 – 2 pc at the distance of the LMC. This is much larger than the typical size of high-mass star-forming cores (∼0.1 pc, Zinnecker & Yorke, 2007). Thus, high spatial resolution observations are required to confirm the spatial scale that are probed by the *AKARI* spectroscopy.

We performed mid-infrared imaging observations toward YSOs in the LMC and SMC with Gemini/T-ReCS (Thermal-Region Camera Spectrograph). The Gemini South telescope in Chile is equipped with the 8.1-meter optical/infrared diameter telescope. Observations were carried out as a part of the Subaru/Gemini Time Exchange Program "Dust and Ices around Extragalactic Young Stellar Objects" (PI. Takashi Shimonishi).

Figure 4 shows an example T-ReCS N-band (7.7 – 13 μm) images of YSOs in the LMC. This is the first mid-infrared observation toward extragalactic YSOs by a ground-based telescope. It can be seen from the figure that no other source is seen around observed sources within a radius of 1.25 pc. In addition, the figure indicates that all the detected sources are almost point sources in the mid-infrared. Measured FWHMs (Full Width at Half Maximum) of N-band images of sources are in the range of 0.4″ ∼ 0.8″, typically ∼0.5″. At the distance of the LMC, 0.5″ corresponds to 0.12 pc, which is very close to a typical size of high-mass star-forming cores (∼0.1 pc, Zinnecker & Yorke, 2007).

Our estimate of ice column densities is based on the absorption band analysis. Since an absorption is seen against the continuum emission, a compact appearance of the infrared continuum emission of the observed YSOs suggests that our *AKARI* spectroscopy probes absorption components toward a small region corresponding to the physical scale of a protostellar core.

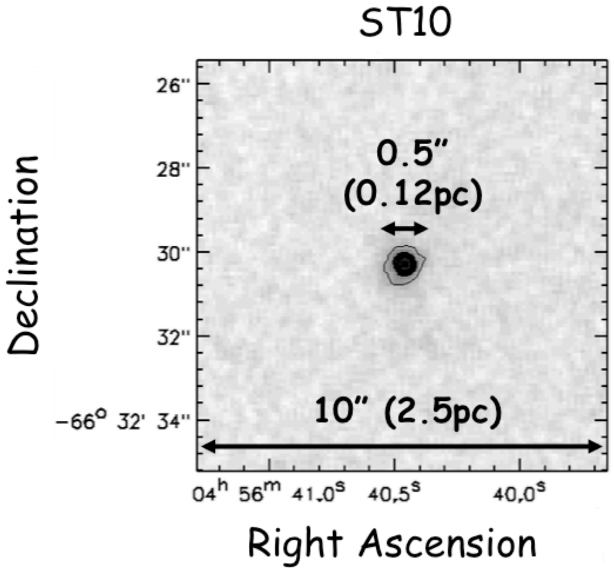

Fig. 4. Example of a Gemini/T-ReCS N-band image of a LMC's YSO. Contour levels are at 20%, 50%, and 70% of peak flux. North is up, east is to the left, and the axes are in J2000 coordinates. The object name and the spatial scale are labeled.

We compare the spatial scale probe by the *ISO*-SWS observation of Galactic high-mass YSOs and that probed by *AKARI* observation of Magellanic YSOs. Typical distances to Galactic massive star-forming regions for which observations of ices were carried out by the SWS are 1 – 2 kpc. Thus the physical scales of Galactic YSOs probed by the spectroscopic aperture of the SWS (14″ × 20″ for 2.5 to 12 μm, de Graauw et al., 1996) are approximately 0.1 – 0.2 pc. This is close to the spatial scale that we probed by the *AKARI* spectroscopy of LMC's and SMC's YSOs. Thus, in terms of the spatial resolution, we can reasonably make a comparative study of Magellanic Cloud's YSOs and Galactic YSOs.

5. SUMMARY

For the last few years, it has been pioneer days for spectroscopic studies of YSOs in the Magellanic Clouds. In this proceeding, we introduce our current research on the infrared observations of ices and dust around embedded YSOs in the LMC and SMC, based mainly on the *AKARI* data. It is shown that ices around YSOs under different galactic environments possess different properties in terms of molecular abundances and column densities. We find a correlation between ice column density and luminosity of YSOs. Also, we discuss the effect of metallicity on the properties of circumstellar ices. The results are quite important if we are to discuss the chemical diversity of circumstellar materials in low-metallicity environment like the early Universe.

For the future, a spectroscopic capability of SPICA or JWST will enable us to investigate the properties of circumstellar materials of lower-mass YSOs in the Magellanic Clouds (e.g., see Sakon et al., 2012 for SPICA/MCS capability). It is also interesting to focus not only on ices and dust but also on gas-phase species, and thus further observations at sub-mm and radio regions with ALMA are highly required. In addition, it is important to interpret the effect of galactic environment on the properties of circumstellar materials from the point of view of theoretical calculations.

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