Observations of Circumstellar Ices around Extragalactic Young Stellar Objects with *SPICA*

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ABSTRACT

Spectroscopic observations with *SPICA* will provide us invaluable opportunities to study the chemical properties of circumstellar solids in various galactic environments beyond the Milky Way. In this proceedings, we discuss scientific importance and feasibility of spectroscopic observations of ices and dust around YSOs in nearby galaxies with *SPICA*.

1. INTRODUCTION

Chemical diversity of materials that forms stars and planets in the universe is one of the important topics of present-day astronomy. Star- and planet-formation activities can occur in various galaxies which differ in many ways such as size, shape and environment. It is thus important to understand how galactic characteristics affect the properties of materials around young stellar objects (YSOs). Particularly, the effect of galactic metallicity on the chemical evolution of interstellar and circumstellar materials is of great interest since cosmic metallicity is increasing with time evolution of the universe. However, observations of YSOs in the early metal-poor galaxies are very difficult due to an enormous distance.

The Large and Small Magellanic Clouds are the nearest low-metallicity galaxies (50 kpc for LMC and 60 kpc for SMC). There are two main reasons to study YSOs in the Magellanic Clouds. First, YSOs in the Magellanic Clouds enable us to investigate how the different metallicity environments affect the properties of circumstellar materials. Metallicities of the LMC and the SMC are known to be approximately 1/2 and 1/5 compared to the solar neighborhood. Next, YSOs in the Magellanic Clouds enable us to investigate the properties of circumstellar materials as a function of the stellar luminosity because the distance to the galaxy is well-determined. Also, the face-on geometry of the LMC allows us to compare the distribution of YSOs and the ISM on a two-dimensional map.

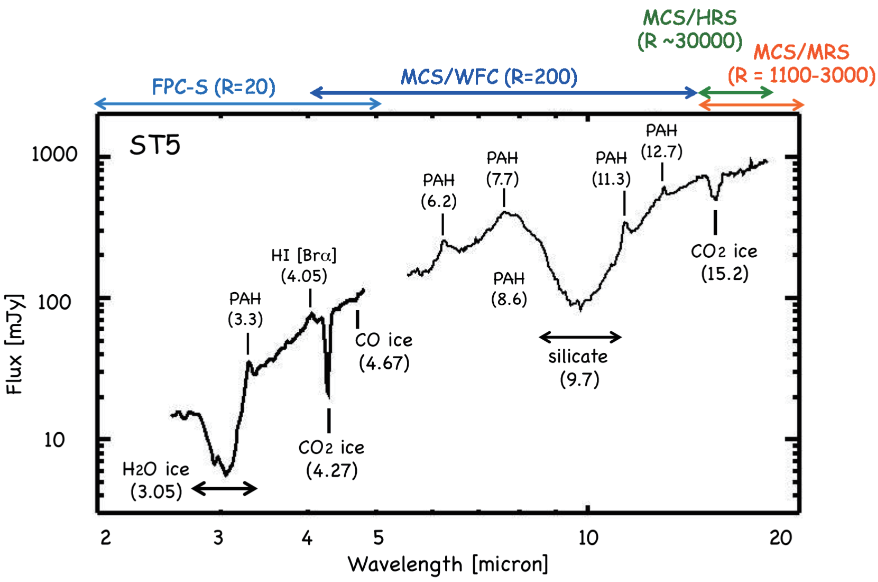

Figure 1. *AKARI*/IRC (thick) and *Spitzer*/IRS (thin) infrared spectrum of an embedded high-mass YSO in the LMC. The positions of detected spectral features are labeled with the central wavelength of each feature in micron. Wavelength coverages of spectroscopic instruments proposed to *SPICA* are also shown. The *AKARI* spectrum is taken from Shimonishi et al. (2010) and the *Spitzer* spectrum is from *Spitzer* Heritage Archive, respectively.

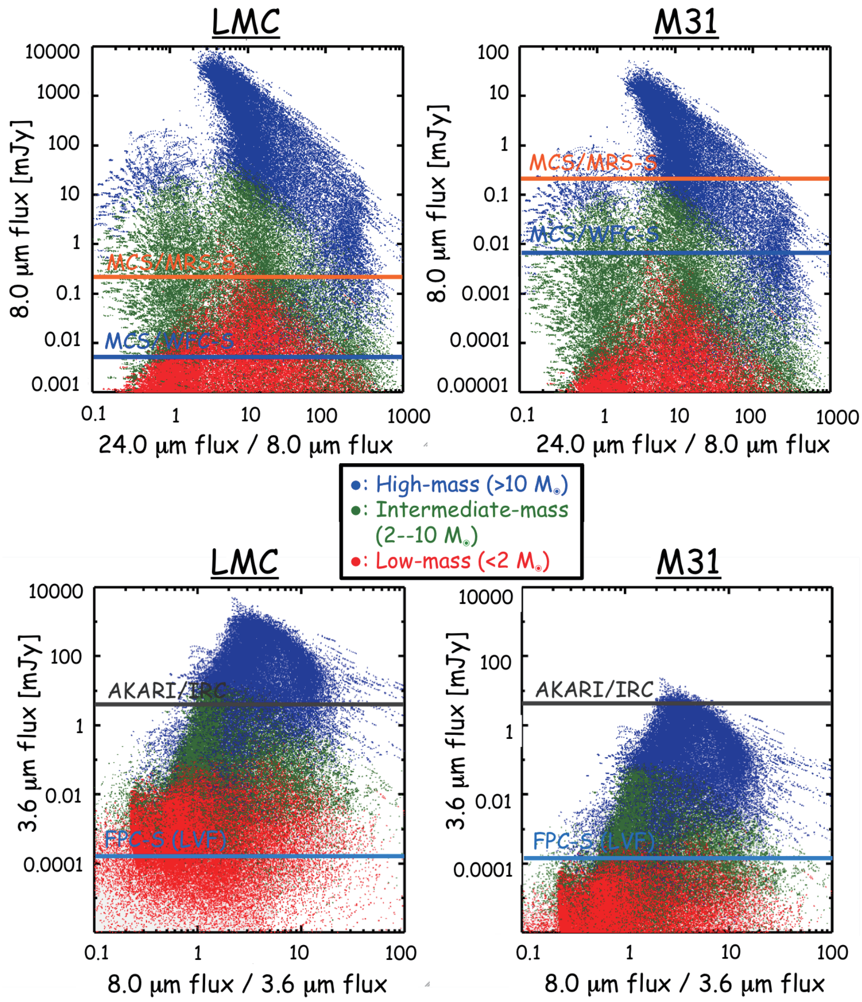

Figure 2. Theoretically-predicted infrared flux and color of YSOs at the distance of the LMC (50 kpc, *left*) and M31 (730 kpc, *right*), based on Robitaille et al. (2007). Plot symbols are color-coded depending on YSOs mass; *blue*: high-mass (>10 $M_\odot$), *red*: intermediate-mass (2–10 $M_\odot$), *green*: low-mass (<2 $M_\odot$). Spectroscopic sensitivities of relevant instruments are indicated by solid lines (*orange*: *SPICA*/MCS/MRS-S, *blue*: *SPICA*/MCS/WFC-S, *grey*: *AKARI*/IRC/NG, *cyan*: *SPICA*/FPC-S/LVF).

Spectroscopic properties of embedded YSOs in the LMC and SMC have been investigated intensively in these few years with the advent of high-sensitivity infrared satellites such as *AKARI* and *Spitzer*. An example of an infrared spectrum of an embedded high-mass YSO in the LMC is shown in Figure 1 together with the spectroscopic capabilities of several instruments proposed to *SPICA*. Near-infrared ice absorption bands are discussed in detail with *AKARI* toward a number of embedded YSO samples in the LMC and SMC (Shimonishi et al. 2008, 2010, 2012; Shimonishi 2012). Mid-infrared ice bands are investigated by *Spitzer* toward a large number of YSO samples (e.g., Seale et al. 2011; Oliveira et al. 2013). These studies have shown that ices around YSOs in the Magellanic Clouds possess different properties in terms of molecular abundances. For example, Shimonishi et al. (2010) reported that the column density ratio of the two major ice species, CO_2/H_2O, is systematically higher in the LMC compared to Galactic counterparts, owing to the harsh radiation environment of the LMC. The results are quite important if we are to understand the chemical diversity of circumstellar materials in various galactic environments, including extremely metal-poor environments as in the early universe.

Ices in dense molecular clouds are considered to be a major reservoir of heavy elements, molecules and various organic compounds that are essential for the presence of life. Chemical reactions on the dust surface are an important process for the formation of molecules in low temperature environment. Solid-state chemistry is also believed to affect various astrochemical phenomena such as hot core/corino chemistry through the sublimation of ice mantles. Therefore, in order to understand the chemical diversity of star-/planet-forming regions in the universe, it is very important to investigate properties of solids in various galactic environments.

2. INFRARED SPECTROSCOPIC STUDY OF EXTRAGALACTIC YSOS IN THE *SPICA* ERA

Currently, spectroscopic observations of YSOs in the LMC and SMC are limited to a portion of high-mass YSOs and achievable spatial resolution is ∼1–2 pc scale for space observations. Significant advances in the infrared spectroscopic capability with *SPICA* will allow us to investigate the chemical properties of solids around extragalactic YSOs in more detail and toward a larger number of samples.

Figure 2 *(left)* shows theoretically-predicted infrared flux and color of YSOs at the distance of the LMC (based on the SED model by Robitaille et al. (2007)). It is shown that infrared spectroscopic sensitivity of *SPICA* MCS enables us to obtain the spectral information of high- and intermediate-mass YSOs in the Magellanic Clouds. The low-resolution spectroscopic mode with FPS-S LVF enables us to detect low-mass YSOs in the LMC. Furthermore, it is possible to obtain spectral information of high-mass YSOs even at the distance of the Andromeda Galaxy (M31) thanks to the high-sensitivity expected for *SPICA* (Figure 2 *right*). *SPICA* will clarify how interstellar environment of the individual galaxy affects the properties of circumstellar materials of YSOs.

Improved spectral resolution of *SPICA* MCS will provide us new knowledge about chemical compositions of ice mantles in diverse extragalactic environments. Currently, the detectable ice species toward extragalactic YSOs are limited to abundant molecules that show relatively strong absorption bands (e.g., H_2O, CO_2, CO). Medium- or high-resolution spectroscopy with MCS allows detailed comparison of observed and laboratory ice profiles and simultaneous analyses of gas-phase absorption lines located near ice absorption bands. This will help shed light on the chemical pathways for molecular formation by solid-state reactions. In addition, *SPICA* should constrain the formation efficiency of complex molecules in ice mantles under low-metallicity environment through the observations minor ice species such as CH_3OH.

3. SUMMARY

Infrared observations of extragalactic YSOs and relevant astrochemical studies are now at the dawn of a new era. In this proceeding, we review a part of scientific results which was obtained in the *AKARI* era and discuss possible future observations with *SPICA*. Massive infrared photometric and spectroscopic databases for the Magellanic Clouds obtained by *AKARI* (Kato et al. 2012; Shimonishi et al. 2013) and *Spitzer* (Meixner et al. 2006; Woods et al. 2011) should help plan unique observation strategies in the *SPICA* era. As a natural extension of infrared studies from *AKARI* to *SPICA*, it will play a very important role for understanding of the chemical diversity of solids in galactic scales.

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