Discovery of Two Infrared Objects with Strong Ice Absorption in the Akari Slitless Spectroscopic Survey of the Galactic Plane

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Abstract
We discover two infrared objects that show deep absorption features of H2O, CO2, and CO ices in the AKARI/Infrared Camera slitless spectroscopic survey of the Galactic plane in 2.5–13 μm. Both objects are neither located in known star-forming regions nor in known dense clouds. For one of the objects, Object 1, we successfully extract spectrum from 2.5–13 μm, which also shows several absorption features in 5–13 μm, including deep silicate absorption at 10 μm. For the other object, Object 2, only spectrum from 3.1–5 μm is reliably extracted due to the presence of nearby overlapping objects and faint nebulosity. Both objects show warm (>100 K) CO gas absorption in addition to the ice absorption features, suggesting that they are embedded young stellar objects (YSOs). On the other hand, both objects have spectral energy distributions (SEDs) that peak at around 5 μm and decrease toward longer wavelengths. These characteristics of the SEDs and the presence of deep absorption features cannot easily be accounted for by standard YSO models. They may be explained as background stars behind dense clouds. We discuss possible nature of the objects and implications of the present discovery.

Unified Astronomy Thesaurus concepts: Interstellar dust extinction (837)

Supporting material: data behind figure

1. Introduction
In cold, dense regions, various kinds of ice species are formed and play significant roles in the interstellar chemistry as well as in the formation of stars and planetary systems (for a review see Boogert et al. 2015). While the Infrared Space Observatory (ISO) provided an extensive spectroscopic database of ice absorption features for massive young stellar objects (MYSO; e.g., Gibb et al. 2004; Dartois 2005) and CO2 ice properties in the Taurus dark cloud (e.g., Whittet et al. 1998; Nummelin et al. 2001), Spitzer, and AKARI as well as ground-based spectroscopy extended the study of ices to low-mass young stellar objects (LYSO) and the various ice species in several dense clouds (e.g., Boogert et al. 2004, 2008, 2011; Bergin et al. 2005; Knez et al. 2005; Pontoppidan et al. 2008; Reach et al. 2009; Öberg et al. 2011; Aikawa et al. 2012; Noble et al. 2013, 2017). Theoretical and experimental studies suggest that ices are formed on the grain surface via diffusive surface reactions or energetic processes such as photolysis or radiolysis (for recent reviews see Hama & Watanabe 2013; Cuppen et al. 2017; Mifsud et al. 2021). Although the formation and evolution processes of ice species in dense regions are not yet fully understood, the profiles of absorption features in the infrared provide us with valuable information on the thermal and energetic processes imposed upon ices as well as on the nature of the objects associated with ice absorption (e.g., Pontoppidan et al. 2003; Öberg et al. 2011; Noble et al. 2013; Boogert et al. 2015). The presence of ice absorption is also thought to be a reliable indicator for the identification of young stellar objects (YSOs; van Loon et al. 2005; Shimonishi et al. 2008, 2010; Seale et al. 2009), which is difficult to be made unambiguously solely by infrared photometric observations because some galaxies and dusty evolved stars have photometric characteristics similar to YSOs (e.g., Gutermuth et al. 2008; Gruendl & Chu 2009; Beerrer et al. 2010; Kato et al. 2012; Koennig & Leisawitz 2014).

H2O, CO2, CO, and CH3OH ices are known to be the major ice species in YSOs and dense clouds, and they have the major bands at 3.0, 6.0, 13.1 (H2O), 4.67 (CO), 4.26, 15.2 μm (CO2), 3.53, 6.76, 8.9, and 9.75 μm (CH3OH) (Gerakines et al. 1995; Gibb et al. 2004, and references therein). Other complex ice species also have characteristic bands in 4.6–10 μm (Gibb et al. 2004; Boogert et al. 2015). Therefore, near-infrared (NIR) and mid-infrared (MIR) spectroscopy is an efficient means to study the properties of interstellar ices as well as the nature of objects associated with ice absorption.

In this paper, we report discovery of two interesting infrared objects that show strong absorption bands of H2O ice at 3.0 μm, CO2 ice at 4.26 μm, and CO ice at 4.67 μm based on a NIR to MIR slitless spectroscopic survey (2.5–13 μm) of the Galactic plane carried out with the Infrared Camera (IRC) on board the AKARI satellite (Onaka et al. 2007). Both objects are neither located in known star-forming regions nor in known dense clouds. They could be runaway YSOs (de Wit et al. 2005; Renzo et al. 2019), which elude past YSO surveys, or located behind unknown compact, dense clouds.

In Section 2, the observations and data reduction are described, and the results are presented in Section 3. Analysis of the spectra is given in Section 4. Possible identification of the nature of the objects is discussed in Section 5 and a summary is given in Section 6.

2. Observations and Data Reduction
The present observations were carried out in the slitless spectroscopic survey mode with the grisms of the IRC, which
had a field of view of $10' \times 10'$ and obtained spectra of point sources for 2.5–13 $\mu$m (Ohyama et al. 2007), as part of the program of the Interstellar Medium in our Galaxy and Nearby galaxies (ISMGN; Kaneda et al. 2009). Spectra of 2.5–5 $\mu$m were taken with the NIR channel of the IRC in the NIR Grism (NG) mode, while those of 5–13 $\mu$m were obtained with the MIR-S channel in the Short-MIR Grism 1 (SG1; 5.0–8.2 $\mu$m) and Short-MIR Grism 2 (SG2; 7.6–13.0 $\mu$m) modes. The spectral resolutions are about 0.03, 0.12, and 0.21 $\mu$m for the NG, SG1, and SG2 modes, respectively (Ohyama et al. 2007).

We surveyed nine regions in the Carina arm, eight in the Crux arm, and five in the Perseus arm. Table 1 summarizes the positions, IDs, and dates of the observations.

Two objects are found in one of the Crux arm regions (target name of CRU-048TO003), which show deep absorption of CO$_2$ ice at 4.26 $\mu$m and CO ice at 4.67 $\mu$m in their slitless spectra of the NIR channel by visual inspection. We call the two objects Object 1 and Object 2 in the following. No similar objects that show strong ice absorption were found in the other two objects Object 1 and Object 2 in the following. No similar spectra of the NIR channel by visual inspection. We call the

Table 1
Observation Log of the Slitless Spectroscopic Survey of the Galactic Plane

| Target Name   | Observation ID | Position$^a$ R.A.(J2000.0) Decl. | Observation Date |
|---------------|----------------|---------------------------------|------------------|
| CAR-079_O001  | 1402304.1      | 09°53'29"                      | 2007 June 29     |
| CAR-079TO002 | 1400201.1      | -5°14'00"                      | 2006 December 29 |
| CAR-079TS004 | 1400203.1      | -5°26'49"                      | 2006 December 29 |
| CAR-079TO003 | 1400197.1      | 10°01'24"                      | 2007 January 22  |
| CAR-079_S002 | 1402301.1      | 13°13'55"                      | 2007 February 06 |
| CAR-057TO005 | 1400229.1      | 13°14'18"                      | 2007 February 07 |
| CAR-057TO003 | 1400225.1      | -6°15'27"                      | 2007 February 07 |
| CAR-057TT001 | 1400231.1      | -65°11'49"                     | 2007 February 06 |
| CAR-057TS002 | 1400215.1      | -62°39'19"                     | 2007 February 10 |
| CRU-048TO003 | 1400259.1      | 14°09'57"                      | 2007 February 13 |
| CRU-048TO002 | 1400257.1      | 14°03'25"                      | 2007 February 13 |
| CRU-048TO004 | 1400261.1      | -61°10'09"                     | 2007 February 13 |
| CRU-048TS001 | 1400247.1      | 14°13'53"                      | 2007 February 15 |
| CRU-048TS003 | 1400251.1      | -61°49'49"                     | 2007 February 15 |
| CRU+032_SP05 | 1410127.1      | 18°48'41"                      | 2007 February 15 |
| CRU+032_S003 | 1410128.1      | 18°59'30"                      | 2007 February 15 |
| CRU+032_SP01 | 1410129.1      | -01°36'49"                     | 2007 February 15 |
| PER+070_S001 | 1410194.1      | 20°49'51"                      | 2007 February 15 |
| PER+070_O001 | 1410177.1      | 20°10'45"                      | 2007 February 15 |
| PER+070_S002 | 1410265.1      | 20°12'59"                      | 2007 February 15 |
| PER+070_O003 | 1410270.1      | 20°14'02"                      | 2007 February 15 |
| PER+070_O002 | 1402369.1      | 20°15'21"                      | 2007 February 15 |

Note.  
$^a$ The intended center position of the field of view.

$^6$ The intended center position of the field of view.

$^7$ https://www.ir.isas.jaxa.jp/AKARI/Archive/Catalogues/PSC/
the NIR and MIR-S channels by using the IRC spectroscopic data reduction toolkit of version 20150331\(^*\) and the latest wavelength calibration for the NIR spectrum was applied (Baba et al. 2016).

In the catalog production process, MIR spectra are extracted for 7 pixels in the spatial direction to not lose the source flux and obtain an optimal signal-to-noise ratio (Yamagishi et al. 2019). We needed to apply a narrower spatial extraction window to avoid contamination in the spectrum extraction of the present data and the aperture corrections were applied based on the point-spread function for the narrow extraction window (Ohyama et al. 2007). The sky background was subtracted using the sky data near the object. Object 1 is located in a relatively empty region of the sky on the Galactic plane, and there is an infrared source located at a distance of about 8″ from Object 1 in the direction vertical to the dispersion (Figure 1). The image quality (FWHM) of the NIR channel is better than 4.3″ (Onaka et al. 2007). The NG spectrum (2.5–5 μm) of Object 1 was extracted for 4 pixels (=5.84″) to avoid the contamination from the nearby source. We, then, applied a two-Gaussian component fit in the spatial direction developed by Sakon et al. (2012) to estimate the contamination of nearby sources (see also Noble et al. 2013). We confirmed that the spectrum extracted by the toolkit agreed with the two-Gaussian component fit within the uncertainty and the contamination was insignificant. We extracted the SG1 and SG2 spectra (5–13 μm) for 3 pixels (=7.02″). The image quality (FWHM) of the MIR-S channel is better than 5.1″ (Onaka et al. 2007). The nearby source is fainter in the MIR (Figure 2) and does not contaminate the SG1 and SG2 spectra of Object 1. The spectra of SG1 and SG2 are smoothly connected at 8 μm and we use the SG1 spectrum for wavelengths shorter than 8 μm and the SG2 spectrum for those longer than 8 μm.

Around Object 2, there are a nearby source with a similar brightness at a distance of 5″ and a source brighter than Object 2 at a distance of 8″ in the direction vertical to the dispersion in the NG image (Figure 2(a)). We applied a two-Gaussian component fit in the spatial direction to estimate the contamination from the nearby sources in the NG spectrum and adopted a narrow extraction window of 2 pixels (=2.92″), which reduced the signal-to-noise ratio but enabled to avoid the contamination for the spectral region 3.1–5.0 μm. We found that it was not possible to reliably recover the spectrum for 2.5–3.1 μm due to the faint continuum with the strong H₂O ice absorption at 3 μm. Object 2 is also located in a region with faint nebulosity in the MIR (Figure 1) and is very faint in the SG2 image. In the SG1 image, it was impossible to avoid contamination from the nebulosity completely and obtain a reliable spectrum even with a narrow extraction window. It was also difficult to select a reliable sky area for the background subtraction. To recover spectral information as much as possible, therefore, the same window size of 3 pixels as for Object 1 was adopted. The spectrum for 5–8 μm taken with the SG1 mode was able to be extracted with low reliability, while the spectrum taken with the SG2 mode (8–13 μm) was very faint and could not be extracted. Therefore, Object 2 has a reliable spectrum extracted only for 3.1–5.0 μm.

During the slitless observations, a 3 μm image and a 9 μm image were taken to provide the origin of the wavelength scale in the slitless images (Ohyama et al. 2007). The absolute wavelength in the spectrum extraction process is estimated to be accurate better than a half pixel, which corresponds to 0.005, 0.03, and 0.05 μm for the NG, SG1, and SG2 spectra, respectively. Lastly, the spectrum between 4.95 and 5.0 μm in the NG was removed because of the potential contamination of the second-order light (Baba et al. 2016).

3. Results

The extracted spectra of Object 1 and Object 2 are shown in Figure 3. For Object 2, the gray lines indicate the regions, where the spectra are affected by nearby sources and faint nebulosity, and are not reliable. There is a small jump between the NG and SG1 spectra of Object 1 at 5 μm. We did not make any correction to stitch the spectra. Photometric data of 2MASS, Spitzer/IRAC and MIPS, WISE, and AKARI are also plotted together. The red circles show the original catalog values, while the purple squares indicate the color-corrected ones, for which the spectral information for color correction is estimated from the observed spectrum. For Object 1 (Figure 3(a)), the color corrections are generally small except for those at the deep absorption features (W1 (3.4 μm), IRAC band 4 (8 μm), and AKARI 9 μm). For Object 2 (Figure 3(b)), the color correction is possible only for IRAC band 2 (4.5 μm). The photometric data are generally in agreement with the observed spectra, suggesting that the spectra are extracted properly.

\(^*\) https://www.ir.isas.jaxa.jp/AKARI/Observation/support/IRC#software

Figure 1. Locations of the two objects that show strong ice absorption features in the AKARI slitless survey. The background is the WISE band 3 (12 μm) image. The yellow dashed rectangle shows the field of view of the IRC observations (10′ × 10′), while the white arrow indicates the upward dispersion direction in the slitless spectrum images shown in Figure 2. The yellow and red circles show the locations of Object 1 and Object 2, respectively. The yellow plus sign indicates an AGB star candidate (2MASS J14042291-6114400, Robitaille et al. 2008), the red pluses show H II regions (1: G311.440-00.424, 2: G311.489+00.394, 3: G311.621+00.295, 4: G311.629+00.289, 5: G311.629+00.277, 6: G311.638+00.30, Beuret et al. 2017), and the blue pluses display star-forming regions (7: IRAS 14000-6104, 8: IRAS 14004-6104, 9: RAGL 4188, Avedisova 2002).
For Object 1, the broad absorption of H$_2$O ice at 3.0 μm is also visible, while that of Object 2 is not clearly seen due to the nearby bright source.

### Table 2

| Properties/Band | Object 1 | Object 2 |
|-----------------|----------|----------|
| 2MASS ID        | J14041323-6112401 | J14042016-6115495 |
| R.A. (J2000.0)  | 14h04m13.2s | 14h04m20.2s |
| Decl.           | -61°12'40.1'' | -61°15'49.5'' |
| J               | >16.712     | >17.548   |
| H               | 14.914 ± 0.11 | >16.880   |
| $K_s$           | 10.346 ± 0.023 | 11.730 ± 0.026 |
| W1              | 8.755 ± 0.023 | 9.600 ± 0.024 |
| W2              | 6.828 ± 0.020 | 7.903 ± 0.020 |
| W3              | 6.699 ± 0.034 | 7.216 ± 0.040 |
| W4              | 5.772 ± 0.066 | >4.615** |
| [3.6]           | 7.676 ± 0.041 | 8.493 ± 0.040 |
| [4.5]           | 6.592 ± 0.056 | 7.888 ± 0.037 |
| [5.8]           | 6.050 ± 0.036 | 7.151 ± 0.037 |
| [8]             | 5.925 ± 0.030 | 7.170 ± 0.029 |
| [24]            | 4.65 ± 0.02  | 6.00 ± 0.33  |
| AKARI 9 μm (mJy)| 119.3 ± 14.6 | <50 |

Notes.

* Photometric data are given in magnitude except for AKARI 9 μm, which is in units of millijansky. The WISE data are taken from the ALLWISE catalog and the IRAC and MIPS data are from the GLIMPSE and MIPS GAL catalogs. The AKARI data are taken from the JAXA/ISAS server (see text).

** We set this value as a lower limit because of the presence of faint nebulosity (see Section 3).

Because of the small jump between NIR and MIR spectra, we fit a quadratic polynomial to the logarithmic of the flux at the continuum regions, and we fit a 1000 K blackbody for Object 1 (Gibb et al. 2004) to the photometry points of IRAC bands 3 and 4, and MIPS 24 μm. No continuum is estimated for Object 2 for wavelengths longer than 200 μm.

### 4. Absorption Features

For Object 1, the spectrum at around 3 μm is very faint and is not reliably extracted as described in Section 2. However, the presence of deep absorption is suggested by the faintness of the flux at around 3 μm and by the decreasing trend of the spectrum from ~3.3 μm. The spectrum of 3.1–5.0 μm shows several absorption features, including CO$_2$ ice at 4.26 μm and CO ice at 4.67 μm. The W4 (22 μm) data are appreciably brighter than the MIPS 24 μm data. Object 2 is associated with faint nebulosity in the MIR region (Figure 1). We attribute the difference to the larger beam of WISE, which is affected by the nebulosity, and take the WISE data point as an upper limit. The nebulosity also affects detection of AKARI 9 μm. Inspection of the original data confirms 50 mJy as a conservative upper limit (Ishihara et al. 2010), which may suggest the presence of silicate absorption. The spectrum of Object 2 at wavelengths longer than 20 μm is not well constrained, and only a decreasing trend similar to Object 1 is suggested.

In addition to the NIR and MIR photometry, we searched for far-infrared (FIR) data of both objects in the Herschel Infrared Galactic Plane Survey data (HIGAL; Molinari et al. 2016). There are no objects listed at the object positions in the HIGAL catalogs. Upper limits of the detection depend on the position of the sky. From the fluxes of objects detected within 2′ of the target positions and the completeness limits of the survey (Molinari et al. 2016), we conservatively estimate upper limits as 0.8, 3, 9, 10, and 10 Jy at 70, 160, 250, 350, and 500 μm, respectively.

9 https://tools.sodc.asi.it/HiGAL.jsp
than 5 μm. The assumed continua are shown by the blue solid lines in Figure 3. The optical depth is estimated using these continua. In the following, we discuss the spectral features in 2.5–4.0, 4.0–5.0, 5.0–8.0, and 8–13 μm, separately. For Object 2, only the features in the reliable spectrum of 4.0–5.0 μm are discussed.

4.1. 2.5–4.0 μm

Figure 4 shows the spectrum of Object 1 in the 2.5–4 μm region. In addition to the deep absorption of H2O ice at 3.0 μm, there are weak features seen at ∼3.4 and 3.54 μm. They can be attributed to O-H stretching modes of CH3OH ice (D’Hendecourt & Allamandola 1986). CH3OH ice also has a stronger band at 3.07 μm. We first fit the features in 3.3–3.6 μm with CH3OH ice and estimate its contribution to the 3.0 μm band. A linear baseline (solid purple line in Figure 4(a)) is subtracted from the observed spectrum and the spectrum in 3.3–3.6 μm is fitted with the absorbance data of pure CH3OH ice at 15 K (Fraser & van Dishoeck 2004) taken from the Leiden laboratory ice database.10 The band profile hardly changes below 100 K and the choice of different temperature data does not affect the fit result. Pure CH3OH ice data fit the observed spectrum reasonably well (Figure 4(b)). From the fit, we estimate the column density of CH3OH ice as (2.6 ± 0.6) × 1017 cm−2, assuming that the band strength of the 3.54 μm band is 7.6 × 10−18 cm molecule−1 (D’Hendecourt & Allamandola 1986). With the estimated

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10 https://icedb.strw.leidenuniv.nl
column density, the contribution of CH$_3$OH ice to the 3 $\mu$m absorption is found to be insignificant (blue dotted line in Figure 4(a)).

Figure 4(b) also suggests the presence of weak features at around 3.4 and 3.47 $\mu$m. The 3.47 $\mu$m feature has been seen in MYSOs, LYSOs, and background stars (Shimonishi et al. 2016, reference therein). It has been attributed to either a C–H vibration mode of hydrogen atoms bonded to tertiary carbon atoms (Allamandola et al. 1992) or to ammonia hydrate formed in NH$_3$:H$_2$O mixture ice (Dartois & d’Hendecourt 2001; Dartois et al. 2002). The 3.4 $\mu$m feature has often been seen in diffuse clouds and could be a sign of hydrocarbons (Sandford et al. 1991; Pendleton et al. 1994; Chiar et al. 2013). The laboratory data of CH$_3$OH fit the 3.4 $\mu$m feature fairly well, and there is no need for a 3.4 $\mu$m hydrocarbon feature. It should, however, be noted that the fit is also dependent on the assumed continuum. Further observations with a higher signal-to-noise ratio are needed to confirm their presence.

A strong extended red wing on the 3.0 $\mu$m H$_2$O ice absorption band is clearly seen in Figure 4(a). While a correlation of the red wing with the column density of H$_2$O ice is suggested for YSOs (Thi et al. 2006), there are objects that show the 3.0 $\mu$m band without the red wing and those with a very strong wing (Noble et al. 2013). The origins of the red wing are still in debate. The red wing and its references are discussed in more detail in Noble et al. (2013) and Boogert et al. (2015). The profile of the red wing of Object 1 is similar to Type 1 in Noble et al. (2013), being typical of YSOs and background stars. In this paper, we do not attempt to fit the red wing. We also avoid the region around the peak of the 3.0 $\mu$m absorption in the fit because of the low signal-to-noise ratio.

We fit the spectrum of the regions of 2.7–2.9 $\mu$m and 3.1–3.2 $\mu$m with the spectrum of amorphous H$_2$O ice. We adopt the optical constants of amorphous H$_2$O ice measured at various temperatures between 20 and 150 K provided by Mastrapa et al. (2009). Because the 3.0 $\mu$m band is strong and broad, it is necessary to take account of the particle shape effect (Ehrenfreund et al. 1997; Noble et al. 2013). We assume a continuous distribution of ellipsoids (CDE) for the shape. The original CDE assumes a flat distribution of the shape, giving equal probabilities to extreme shapes, i.e., infinitely narrow needles or thin disks (Bohren & Huffman 1983). In this paper, we assume a shape distribution with a peak at a sphere (Ossenkopf et al. 1992) as a more realistic distribution. The difference in the assumed distribution is small and does not affect the following results.

The amorphous H$_2$O ice at 60 K is found to show the best fit to the observed spectrum (red solid line in Figure 4(a)). The amorphous H$_2$O ice at 15 K has a peak at a shorter wavelength and cannot fit the longer wavelength side of the observed profile very well (green long dashed line), while the one at 100 K shows a sharper peak due to partial crystallization, which does not fit the observation either (light blue short dashed line). Note that the fits have a larger weight on the 2.7–2.9 $\mu$m because of the higher signal-to-noise ratio than in 3.1–3.2 $\mu$m. The present analysis suggests that the H$_2$O ice toward Object 1 is accounted for by amorphous ice, which is thermally processed to some extent. The column density of H$_2$O ice is estimated from the integrated band strength as $(54.9 \pm 1.1) \times 10^{17}$ cm$^{-2}$, assuming that the band strength is given as $2.1 \times 10^{-16}$ cm molecule$^{-1}$ for the amorphous H$_2$O ice at 60 K (Mastrapa et al. 2009).

For Object 2, the spectrum between 3.1 and 4.0 $\mu$m is extracted without contamination. However, this spectral range of Object 2 is much fainter than that of Object 1 (Figure 3) and thus noisy. No features are clearly seen in this spectral range and we do not discuss it in this paper.

### 4.2. 4.0–5.0 $\mu$m

Figure 5 shows the 4.0–5.0 $\mu$m spectra of the optical depth for Object 1 and Object 2, which indicate the presence of several absorption features. H$_2$O ice is known to have a broad, shallow feature of a combination mode at around 4.5 $\mu$m (Hagen et al. 1981). Its contribution is estimated from the column density determined from the absorption at 3.0 $\mu$m (brown dotted–dashed line) and taken into account in the
The temperature of the CO gas is obtained with 150 K. We assume the same estimated from the 3.0 \( \mu m \) component is not included in the shoulder and red wing without XCN component. Therefore, the feature is relatively strong. The CO gas can account for both the blue shoulder and red wing, and thus the XCN component is required to account for Object 1.

The best-fit results are shown by the red solid lines in Figure 5. The column densities and the peak wavelengths in the best fits are summarized in Table 3. For CO2 ice, the peak wavelength is found to be shorter than 4.26 \( \mu m \) for both objects (Table 3). While the 4.4 \( \mu m \) broad component shifts the peak wavelength of the CO2 component slightly, the observed peaks are always seen at a wavelength of 4.26 \( \mu m \) or shorter. Therefore, the peak is clearly shorter than the peak position of apolar CO2 ice of >4.26 \( \mu m \), suggesting that a nonnegligible fraction of CO2 ice is either polar or pure (Ehrenfreund et al. 1997). For CO ice, the absorption feature is observed at 4.66–4.67 \( \mu m \), which agrees with pure CO ice. Polar CO ice has a peak at a wavelength longer than 4.68 \( \mu m \) and does not match with the observed spectra (Ehrenfreund et al. 1997). The differences in the peak wavelengths are smaller than the spectral resolution (\( \sim 0.03 \mu m \)), but comparable with the resolution per pixel (\( \sim 0.01 \mu m \)). They are larger than the
uncertainty in the wavelength (~0.005 μm, see Section 2). High-spectral resolution observations are needed to confirm the properties of the CO and CO2 ices accurately.

The column densities of CO and CO2 ices are estimated from the absorption features at 4.67 and 4.26 μm, assuming that the band strenghts are 1.1 and 7.6 × 10^{-17} cm molecules^{-1}, respectively (Gerakines et al. 1995). Since both features are deep, and narrower than the spectral resolution, we need to take account of the saturation effect of the low spectral resolution. We simulate the features in a way similar to Shimonish et al. (2010), assuming that the bandwidth (FWHM) is 18 and 9.71 cm^{-1} for the CO2 and CO features, respectively (Gibb et al. 2004), and estimate the correction factors. The correction factors are found to be 1.19 and 1.16 for the CO2 absorption feature for Object 1 and Object 2, respectively, and 1.19 and 1.27 for the CO feature for Object 1 and Object 2, respectively. Using these correction factors, we estimate the column densities of CO and CO2 ices as shown in Table 3.

The XCN feature is known to consist of two components, 4.60 and 4.62 μm. The 4.62 μm component is securely assigned to OCN− (van Broekhuizen et al. 2005), while the carrier of the 4.60 μm component is unknown. The present data show a peak at 4.60 μm. However, the peak wavelength depends on the assumed CO gas temperature to some extent. With a higher CO gas temperature, the peak shifts to a longer wavelength. Since the present spectral resolution is not enough to resolve the XCN feature and the CO gas rovibrational transitions, it is not possible to discuss the details of the XCN component. We assume the same band strengths for both components as 1.3 × 10^{-16} cm molecule^{-1} (van Broekhuizen et al. 2004; Öberg et al. 2011) and estimate the column density. Since the feature is shallow and broad, we do not apply any correction for the saturation effect. Fits with the CO gas of temperatures different from 150 K always provide a higher XCN abundance. Thus, the estimated XCN abundance should be taken as a lower limit. The results are summarized in Table 3. For the 4.4 μm feature, the integrated band intensities ( = \int \tau \, d\nu) in units of cm^{-1} are given in Table 3.

Figure 6 shows the optical depth spectrum of Object 1 in the region 5.0–8.0 μm. The observed spectrum is indicated by the black solid line with the error bars. The contribution of H2O ice estimated from the 3.0 μm band and that of CH3OH ice estimated from the 3.54 μm band are indicated by the brown dotted–dashed line and the blue dotted line, respectively. The red solid line shows the best-fit result with the summation of the C1, C2, C3, and C4 components for the spectra, from which the contribution from H2O ice has been removed, but that of CH3OH has not (see text). The purple, gray, orange, and green solid lines indicate the C1, C2, C3, and C4 components, respectively.

4.3. 5.0–8.0 μm

Figure 6 shows the optical depth spectrum of Object 1 in the 5.0–8.0 μm, which shows absorption features at around 6 and 6.8 μm. Boogert et al. (2008) decompose the ice features in this spectral range into five distinct components: C1 (5.84 μm), C2 (6.18 μm), C3 (6.755 μm), C4 (6.943 μm), and C5 (a broad component covering 5.8–8 μm). Possible carriers are discussed in detail in Keane et al. (2001); Boogert et al. (2008), and Öberg et al. (2011). The C1 component has been attributed to H2O, H2CO, and HCOOH ices. We assume the

Table 3

| Species         | Column Densities (×10^{17} cm^{-2}) | Abundance (%) | Peak Wavelength (μm) | Column Densities (×10^{17} cm^{-2}) | Peak Wavelength (μm) |
|-----------------|------------------------------------|---------------|----------------------|------------------------------------|----------------------|
| H2O ice         | 54.9 ± 1.1                         | 100           | 3.06                 | ...                                | ...                  |
| CO2 ice         | 6.5 ± 0.2                          | 11.8 ± 0.4    | 4.25                 | 5.3 ± 0.3                          | 4.26                 |
| CO ice          | 12.7 ± 1.0                         | 23.1 ± 2.0    | 4.66                 | 19.5 ± 1.5                         | 4.67                 |
| CO gas          | 28.0 ± 5.3                         | 51.0 ± 9.6    | ...                  | 109 ± 4                            | ...                  |
| XCN             | 0.9 ± 0.1                          | 1.7 ± 0.2     | 4.60                 | ...                                | ...                  |
| CH3OH ice       | 2.6 ± 0.6                          | 4.8 ± 1.0     | 3.54                 | ...                                | ...                  |
| 4.4 μm feature  | 37.8 ± 1.4                         | ...           | 4.38                 | 63.1 ± 1.8                         | 4.38                 |
| C1              | 0.25 ± 0.04                        | ...           | 5.84                 | ...                                | ...                  |
| C2              | 0.23 ± 0.02                        | ...           | 6.18                 | ...                                | ...                  |
| C3              | 0.29 ± 0.03                        | ...           | 6.755                | ...                                | ...                  |
| C4              | 0.39 ± 0.03                        | ...           | 6.943                | ...                                | ...                  |
| Silicate        | 2.9 ± 0.3                          | ...           | 9.7                  | ...                                | ...                  |

Notes.
* Relative abundance to H2O ice.
* Upper limit because of the possible contribution from H2CO ice (see text).
* Intended band intensity ( = \int \tau \, d\nu) in units of cm^{-1}.
* Peak optical depth.
H₂O ice column density from the 3.0 μm fit and estimate its contribution (brown dotted–dashed line). The band of H₂O ice shifts to a longer wavelength and the peak intensity increases, when H₂O ice is diluted by CO₂ (Knez et al. 2005). To be consistent with the fit of the 3.0 μm band, however, we use the same pure amorphous H₂O ice data at 60 K in the fit. There is also a weak feature of CH₃OH ice at around 6.8 μm. Its contribution is estimated from the 3.54 μm band (Figure 4), which is found to be insignificant compared to the observed feature (blue dotted line). After subtracting only the contribution from H₂O ice as in Boogert et al. (2008), we fit the spectrum with the C1, C2, C3, and C4 components simply assuming that they are approximated by Gaussians with the central peak wavelengths and the FWHMs given by Boogert et al. (2008) convolved with the IRC spectral resolution (0.12 μm). Because of the low spectral resolution of the present spectrum, detailed band profiles do not affect the fit results. The four-component fit is shown by the red solid line, which reproduces the observed spectrum fairly well. The present fit does not require the C5 component, but it is difficult to confirm the presence or absence of the C5 component from the present spectrum because of the uncertainty in the assumed continuum. The peak optical depths of the four components in the best fit are shown in Table 3. The contribution of amorphous H₂O ice is estimated to be about a half (∼54%) of the 6.0 μm feature. There seems to be also a feature at around 7.3–7.5 μm. It is weak and its presence has to be confirmed by further observations.

4.4. 8.0–13.0 μm

Figure 7(a) shows the optical depth spectrum of Object 1 for 8.0–13.0 μm together with the contributions from H₂O ice (brown dotted–dashed line) and CH₃OH ice (blue dotted line) estimated from the 3.0 and 3.53 μm bands, respectively. The contribution from CH₃OH ice is negligible, while H₂O ice adds broad absorption at wavelengths longer than 10 μm. The spectrum shows deep absorption at around 10 μm attributable to amorphous silicate. We estimate the optical depth at 9.7 μm, τ₀₇, as 2.9 ± 0.3 after subtracting the contributions from H₂O and CH₃OH ices. In addition, there seems some excess absorption at around 11 μm on the smooth absorption feature of amorphous silicate. Wright et al. (2016) report that similar excess is seen toward YSOs and in the interstellar medium (ISM), attributing it to crystalline forsterite. Do-Duy et al. (2020) make a thorough study of this feature in the various lines of sight and show the ubiquitous presence of the feature in YSOs and even in the diffuse ISM. They discuss several possible origins of the feature in detail, concluding that it arises from crystalline silicate. Do-Duy et al. (2020) use the spectral regions 9.9–10.2 and 12.0–13.0 μm to estimate the amorphous component and extract excess absorption. Since the spectral region of 9.9–10.2 μm of the present spectrum is very noisy, we fit instead the spectral regions 8.9–10.3 and 12.0–13.0 μm by a quadratic equation and extract the excess absorption (Figure 7(b)). The equation fits the spectrum in 9.9–10.2 μm reasonably well, and the different choice of the spectral region for the fit does not affect the extracted excess and the following discussion. The red line in Figure 7 indicates the average excess profile derived in Do-Duy et al. (2020). Note that the actual profile has some asymmetry, which varies from object to object. In Figure 7, a Gaussian with the average peak wavelength (11.08 μm) and the average FWHM (0.76 μm) is simply plotted to show an approximate profile of the average excess. The amplitude is scaled to that of Object 1. The excess of Object 1 peaks at around 11.3–11.5 μm, which is slightly longer than the peaks derived by Do-Duy et al. (2020), particularly compared to those found in the ISM (∼11.1 μm). Note that some YSOs show peaks at longer wavelengths (up to ∼11.2 μm). The ratio of the excess to the silicate absorption at 9.7 μm (0.13 ± 0.06) is also larger, but is roughly in agreement with those found in YSOs (∼0.05) and the diffuse ISM (∼0.04, Do-Duy et al. 2020) within the uncertainty.
We found two intriguing objects that show deep ice absorption features in the AKARI/IRC spectroscopic survey of the Galactic plane. To investigate the nature of the objects and the location of the ice species, we discuss their ice properties and infrared SEDs in the following sections.

5.1. Properties of Absorption Features

Ice absorption features have been observed toward YSOs and used as a good indicator for the identification of YSOs (van Loon et al. 2005; Shimonishi et al. 2008, 2010; Seale et al. 2009). On the other hand, ice absorption is also observed toward background stars sitting behind quiescent, dense clouds (e.g., Knez et al. 2005; Whittet et al. 2007; Boogert et al. 2011; Chiar et al. 2011; Noble et al. 2013). Therefore, they are not secure evidence for the identification of YSO nature of the present objects. In this section, we discuss possible evidence for thermal processing on ices, which is not expected for the features in background stars and thus supports the YSO identification of the objects, based on their spectra.

The 3.0 μm H₂O ice absorption feature of Object 1 peaks at 3.06 μm, which is longer than amorphous H₂O ice at 15 K (~3.02 μm, Figure 4(a)). The difference is small, but is larger than the uncertainty in the wavelength (~0.005 μm). The absorption profile of 15 K H₂O ice does not fit the absorption profile at the longer wavelength side well, which requires a contribution from warm amorphous H₂O ice of thermally processed. The shape effect does not account for the difference and the low spectral resolution does not affect the characteristics of the band profile either.

Gibb et al. (2004) analyze the 3.0 μm of H₂O ice for a number of MYSOs and show that some of them require a warm (≥50 K) ice component in addition to the 10 K component. Boogert et al. (2011) presented spectra of the H₂O ice absorption at 3 μm for several background stars, suggesting no variations in the band profile. The 3 μm absorption features of background stars have a peak between 3.0 and 3.1 μm, similar to Object 1. Figure 8 shows a comparison of the 3 μm optical depth spectrum of Object 1 with those of a YSO (AFGL 2136, Gibb et al. 2004) and a background star (2MASS J1872690-0438406, Boogert et al. 2011). The background star shows a wider profile in the blue side than the YSO and Object 1. Other background stars in Boogert et al. (2011) show similar characteristics. At the red side, no difference is seen between the YSO and the background star, and Object 1 shows a slightly narrower width. The wider width at the blue side of the background star may be attributable to the presence of cold, amorphous ice. The H₂O ice profile of Object 1 is in better agreement with the YSO spectrum, but the difference in the profile between the YSO and the background star is not very large. It should also be noted that large H₂O ice dust shifts the peak to a longer wavelength (Smith et al. 1989). While it cannot be ruled out that the longer wavelength of peak absorption of the 3 μm feature could be accounted for by large dust, the 60 K amorphous ice of a CDE fits the observed spectrum reasonably well, suggesting that the observed 3.0 μm band profile can also be attributed to thermally processed H₂O ice toward Object 1.

The spectra of 4–5 μm contain ample information on the properties of ice species. The abundance of CO₂ ice (relative to H₂O ice) is 11.8% ± 0.4% for Object 1. It is in the range for MYSOs, and at the lowest end of the abundance distribution of LYSOs and lower than the range of background stars (Boogert et al. 2015). Therefore, this abundance ratio suggests that Object 1 may be an MYSO, although this is not definitive evidence, taking account of the distribution of the abundance and the uncertainty in the abundance estimation.

On the other hand, CO ice abundance is large (23.1% ± 2.0%) for Object 1 and its column density is large compared to CO₂ ice for Object 2. This is a secure result since the observed spectra of both objects show very deep absorption at 4.67 μm despite the low spectral resolution. The CO ice abundance is expected to decrease in a higher temperature environment because of its low sublimation temperature (~20 K). The median abundance of CO ice in MYSOs is smaller than that in LYSO and background stars, but the CO ice abundance has a wider distribution than that of CO₂ ice (Boogert et al. 2015). The observed abundance is in a typical range for LYSOs and background stars, while it is still in the range of the abundance distribution of MYSOs (Boogert et al. 2015).

The band peak positions of CO ice suggests that it is pure CO ice, while that of CO₂ ice suggests that it is either pure or polar. At an early phase of ice formation, CO₂ ice is thought to be formed concurrently with H₂O ice and thus it should be polar. At some point, most of frozen-out CO is no longer converted into CO₂ ice and the abundance of CO ice increases (Öberg et al. 2011). The observed large abundance of CO ice suggests that both objects may be in this evolutionary stage. The suggested properties of pure CO and polar CO₂ ices are compatible with this interpretation, although the present spectra do not have a sufficient spectral resolution to discuss their profiles in detail.

The presence of warm CO gas component is a strong indicator for the presence of an embedded heating source. Warm CO gas (>50 K) has been observed in absorption toward embedded YSOs (Pontoppidan et al. 2003; Aikawa et al. 2012). In dense clouds, the gas temperature is supposed to be as low as 20 K and warm CO gas has not been observed in background stars (Noble et al. 2013). For Object 1, the red wing of the 4.67 μm band can be best accounted for by warm CO gas.
integrated optical depths of the C4 to C3 components, suggests that the presence of warm CO gas (∼150 K) is a secure conclusion. CH$_3$OH ice is believed to form on grain surfaces and several different formation processes are proposed by laboratory experiments, i.e., ultraviolet photolysis, radiolysis, and CO hydrogenation (e.g., Hudson & Moore 1999; Watanabe et al. 2007). Large amounts of CH$_3$OH ice have been observed only toward YSOs and very dense cores that are likely to form stars (Boogert et al. 2011), and it could be a good indicator of YSOs (An et al. 2009, 2017). However, the CH$_3$OH ice abundance of Object 1 is in the range of YSOs and such background stars, although a factor of ∼5 less than the most extreme YSO cases. Thus, it does not seem to be a secure indicator of the YSO nature of the objects unambiguously (Boogert et al. 2008, 2011; Boogert et al. 2015). The XCN abundance in Object 1 depends on the assumed temperature of CO gas, and the present result provides a lower limit (Section 4.2). Higher spectral resolution data that resolve rovibrational bands of the CO gas lines and XCN feature are needed to estimate the properties of the CO gas and the XCN abundance accurately (e.g., Pontoppidan et al. 2003).

The features in 5.0–8.0 μm (C1–C5) can also be used to study the thermal processing of ices (e.g., Boogert et al. 2011). The C1–C4 components are present in all classes of objects (MYSOs, LYSOs, and background stars) and their strengths typically correlate well with the H$_2$O column density. The mere presence of these feature therefore can neither support nor rule out the YSO nature of the objects unambiguously (Boogert et al. 2008; Öberg et al. 2011). However, the ratio of the C4 to C3 components is large toward some YSOs, shifting the 6.85 μm feature to a longer wavelength, compared to background stars (Keane et al. 2001; Boogert et al. 2008; Boogert et al. 2011; Reach et al. 2009). Figure 9 plots the H$_2$O ice column density normalized by the peak optical depth of the silicate band (a measure of the H$_2$O ice abundance) against the ratio of the integrated optical depths of the C4 to C3 components, τ(C4)/τ(C3), for Object 1 together with those of the YSO and background star samples taken from Boogert et al. (2008, 2011). Object 1 shows a relatively low H$_2$O ice abundance and the ratio of the C4 to C3 components larger than the majority of background star samples (blue triangles). It is located in the region occupied mostly by YSOs. It should be noted that the C5 component has not been observed toward background stars (Öberg et al. 2011). The present spectrum is not sufficient to confirm the presence of the C5 component.

The observed silicate absorption at 10 μm in Object 1 shows excess absorption at around 11.3 μm and it is best ascribed to crystalline silicate. The excess is detected in YSOs as well as in the diffuse ISM. In the ISM, crystalline silicates are thought to be gradually amorphized by cosmic-ray hits (Brina et al. 2007). Therefore, the presence of the excess itself cannot distinguish YSOs from background stars. A larger amount of excess is sometimes seen toward embedded YSOs, which can be attributed to thermal processing of amorphous silicate by the radiation from the YSO (Do-Duy et al. 2020). The observed relatively large excess may suggest MYSO origin. Further observations of the 10 μm band are needed to estimate the amount of the excess accurately.

Figure 10 shows a correlation of the peak optical depth at 9.7 μm, τ$_{9.7}$, against that at 3.0 μm, τ$_{3.0}$. The black solid line shows a correlation line for the data of background stars (Boogert et al. 2011). Object 1 is shown by the red circle. The green squares and blue triangles indicate the data for YSOs and background stars, respectively, taken from Boogert et al. (2008, 2011).
The SED of embedded YSOs generally increases toward longer wavelengths\((\mu \text{m})\), and decreases toward longer wavelengths, resembling the well-above-the-correlation-line at a large \(\tau_{3.0} \sim 0.6–1.0\) are those toward the core L 328, which may trace diffuse ISM rather than dense clouds (Boogert et al. 2011).

The difference in abundance of various ice species among MYSOs, LMYsOs, and background stars is not very large and their abundance distributions have overlapping ranges (Öberg et al. 2011; Boogert et al. 2011, 2015). Therefore, it is difficult to draw a definite conclusion on the nature of the two objects from the abundance of ice species. On the other hand, there is no evidence against the YSO identification for both objects. Several lines of evidence indicate that Object 1 may be a (M) YSO. The presence of warm CO gas and XCN feature and the relatively large C4 to C3 component ratio in Object 1 support the YSO nature together with the skewed profile of the 3.0 \(\mu\text{m}\) H\(_2\)O ice. Object 2 has less evidence because of the limited range of the reliable spectrum, but the strong blue shoulder of the CO ice absorption feature suggests the presence of a large amount of warm CO gas toward Object 2, supporting that Object 2 is also a YSO.

5.2. SED

The SEDs of both objects peak at around 5 \(\mu\text{m}\) (Figure 3). The SED of embedded YSOs generally increases toward longer wavelengths (e.g., Gibb et al. 2004; Boogert et al. 2008), while that of background stars peaks at wavelengths shorter than 4 \(\mu\text{m}\) (Boogert et al. 2011; Noble et al. 2013). There are, however, a few YSOs whose SED has a peak at around 5 \(\mu\text{m}\) and decreases toward longer wavelengths, resembling the SEDs of Object 1 and Object 2 (e.g., B 35A in Noble et al. 2013).

Figure 11 shows a two-color diagram of Spitzer IRAC and MIPS [3.6]–[5.8] versus [8.0]–[24] for YSOs in the NGC 1333 region taken from Gutermuth et al. (2008). The distribution of YSOs in the Cygnus X region (Beerrer et al. 2010) is also indicated by the dashed lines. Object 1 and Object 2 are located outside of the YSO regions in the two-color diagram. They are too blue in 8–24 \(\mu\text{m}\) compared to standard YSOs. The reddening vector shown by the green arrow suggests that they are rather background stars with large extinction. Taking the relation \(A_{\nu}/\tau_{9.7} = 18.5 \pm 2.0\) (Draine 2003), the visual extinction \(A_V\) is estimated as 54 ± 8.

The WISE colors also confirm the background characteristics of both objects. The WISE colors of Object 1, \(W1-W2 = 1.927 \pm 0.030\) and \(W3-W4 = 0.927 \pm 0.074\), are located well outside of the YSO region in the classification scheme of Koenig & Leisawitz (2014). The color \(W1-W2\) is very red, but \(W3-W4\) is not, suggesting that it is a background star with large extinction. Object 2 has \(W1-W2 = 1.697 \pm 0.031\) and \(W3-W4 = 2.601 \pm 0.057\), which place it in the YSO region. However, as described in Section 3, W4 is much brighter than MIPS 24 \(\mu\text{m}\) data (Figure 3). It may have to be taken as an upper limit because of the presence of nebulosity. If we use MIPS 24 \(\mu\text{m}\) data as a replacement of W4, then Object 2 will be placed outside of the YSO region.

The visual extinction toward the regions of both objects is, however, estimated to be less than 10 based on the optical data (Dobashi et al. 2005) and no thick CO clouds have been detected toward them (Dame et al. 1987; Bronfman et al. 1989). No dark clouds are listed at the positions of the two objects in the Spitzer dark cloud catalog either (Peretto & Fuller 2009). Faint nebulosity is present around Object 2 (Section 3), whose surface brightness is estimated as 10 M\(\text{Jy}\) \(\text{sr}^{-1}\) at 24 \(\mu\text{m}\). According to the ISM dust emission model of Compiègne et al. (2011), this brightness corresponds to the hydrogen column density of \(\sim 5 \times 10^{22} \text{cm}^{-2}\) or \(A_V\) of about 25, if the incident radiation field intensity \(U\) is similar to the solar neighborhood. If the radiation field is stronger, \(A_V\) becomes smaller. The geometry of the nebulosity relative to Object 2 is not known and it is not clear if ice species can be formed in the nebulosity. No nebulosity is seen around Object 1 (Figure 1). While the nebulosity could be the origin of the extinction for Object 2 in part, it seems unlikely that Object 1 is a background star with large extinction unless there is an unknown very small, but thick cloud on the line of sight.

The blue nature of the objects is also confirmed by the comparison with YSO SED models by Robitaille (2017). No YSO models fit the observations of both objects satisfactorily. The best results are obtained with background stars with large extinction (\(A_V \sim 50\)) . Since the models by Robitaille (2017) do not include ice absorption, we compare the present observations with edge-on disk models, in which ice absorption is included (Crapsi et al. 2008), to understand the origin of the discrepancy. Detailed modeling is not the purpose of this paper and only comparison of the SED of Object 1 with some example models is shown in Figure 12. The same discussion can be applied for Object 2.

In Figure 12, the edge-on disk models of the inclination angle of 45° with different envelope masses (Crapsi et al. 2008) are shown by the solid lines together with the observations (black circles). Models with other inclination angles show a similar trend. The blue, red, and green solid lines show examples of the models with the envelope masses of 0.55, 1.5, and 4 \(M_{\odot}\), respectively, normalized at 4.6 \(\mu\text{m}\). The observed depth of ice absorption can be best reproduced by the model.
Figure 12. SED of Object 1 and examples of edge-on disk models (Crapsi et al. 2008) in units of $\nu F_\nu$. The black circles show the observed photometric points. Note that the data at 1.2, 70, and 160 $\mu$m are upper limits. The edge-on models of the inclination angle of 45˚ are scaled at 4.6 $\mu$m and shown by the solid lines for the envelope masses of 0.55 (blue), 1.5 (red), and 4 $M_\odot$ (green). with the envelope mass of 1.5 $M_\odot$ (red line) among them and it fits the observations up to 12 $\mu$m generally well. However, for wavelengths longer than 20 $\mu$m, the model SED starts deviating from the observations. The model SED is either flat (blue) or increasing (red and green), while the observed SED decreases. Note that both objects are not detected in the HIGAL survey (Molinari et al. 2016) and the plotted upper limits are very conservative. If we decrease the envelope mass (blue line), it slightly reduces the discrepancy, but the ice absorption features become shallower and does not match the observations very well. Models with smaller inclination angles show shallower ice absorption and do not reproduce the observations. The edge-on disk with a large inclination angle is optically thick at wavelengths shorter than 5 $\mu$m, but becomes optically thin at longer wavelengths. The absorbed energy in the disk is emitted at wavelengths longer than 20 $\mu$m. Therefore, it is a natural consequence that edge-on disk models with large inclination angles and deep absorption show strong MIR and FIR emission relative to the NIR. Absorption occurs on the line of sight, while emission comes from the entire envelope. If the absorbing envelope is very clumpy and located just on the line of sight, the MIR to FIR emission is reduced, which could be reconciled with the observed SEDs. Asymmetric, clumpy distributions of dust are sometimes seen in protoplanetary disks and transition disks (e.g., Fujiwara et al. 2006; van der Marel et al. 2013) and thus may not be unusual for YSOs. If the outer radius is truncated, it could also reduce the FIR emission. Further investigations on modeling are needed to understand the SEDs of the present objects.

5.3. Nature of the Objects and Implications

Both objects show features at both the blue and red sides of the CO ice feature at 4.67 $\mu$m and they are attributed to the absorption of warm CO gas. Warm CO gas is not expected to be present in quiescent, dense clouds and thus is strong evidence for the YSO identification (Pontoppidan et al. 2003; Aikawa et al. 2012; Noble et al. 2013; Onaka et al. 2016). The relatively large abundance of XCN estimated for Object 1 also supports the YSO characteristics since XCN has never been observed in background stars and the estimated abundance is rather high compared to the upper limits for background stars (Öberg et al. 2011; Boogert et al. 2015). Further observations with high-spectral resolution are needed to resolve the CO gas and XCN features and estimate their properties unambiguously. There are other pieces of evidence to support the YSO identification for Object 1, including an indication of thermally processed amorphous H$_2$O ice and the abundance of CO$_2$ ice, but none of them is very secure evidence since similar characteristics are also observed in background stars. There is no strong evidence against the YSO identifications for the both objects in the characteristics of ice absorption features.

On the other hand, the SEDs of both objects are rather blue in 8–24 $\mu$m, which put them outside of the standard YSO region in the two-color diagram (Figure 11). The blue nature and nondetection at FIR suggest that they are background stars with large extinction. Since there is no evidence for the presence of dense clouds in optical and CO observations, those clouds must be very compact. The presence of such isolated dense, compact clouds is not known. If the two objects are background stars, it will make an impact on our view of the dense gas distribution in our galaxy and low-temperature chemistry in the ISM.

H$_2$O ice has also been observed in O-rich AGB stars with high mass-loss rates (OH/IR stars) and post-AGB stars with dense, cooled envelopes (e.g., Gillett & Soifer 1976; Omont et al. 1990; Sylvester et al. 1999). Their SEDs have a peak at around 10 $\mu$m and decreasing toward longer wavelengths (Omont et al. 1990; Demyk et al. 2000). The WISE color W2–W3 of Object 1 and Object 2 is 0.129 ± 0.039 and 0.687 ± 0.044, respectively, which is very blue compared to the W1–W2 color, and only a few evolved stars are located in this region of the two-color diagram (Koenig & Leisawitz 2014). The 3 $\mu$m H$_2$O ice features in those O-rich evolved stars show a narrower profile than those of YSOs (Gillett & Soifer 1976) or have peaks at 3.1 $\mu$m, indicating that a significant fraction of H$_2$O ice is crystalline (Maldoni et al. 2003). While recent models show that complex organic ices can be formed in C-rich evolved stars (Van de Sande et al. 2021), features of other ice species have not been detected in O-rich evolved stars with H$_2$O ice absorption probably because of carbon-poor environments (Sylvester et al. 1999). Therefore, it is not very likely that the present objects are evolved stars. Absorption features of various ice species are also detected in starburst galaxies and dust-enshrouded active galactic nuclei (e.g., Spoon et al. 2000, 2003, 2004; Imanishi et al. 2010; Yamagishi et al. 2013, 2015). They are usually associated with the 3.3 $\mu$m emission of aromatic species and/or emission of hydrogen recombination lines. Since the present objects are located on the Galactic plane and do not show these emission features, it is not likely that they are galaxies either.

If the background star is M-type, it could account for the observed absorption of CO gas. However, M-type giants show a much broader CO absorption feature starting from 4.3 $\mu$m and extending up to 4.9 $\mu$m (Heras et al. 2002) due to the high temperature of the CO gas in their atmosphere (≥3000 K). M-type dwarfs show the dominance of higher-level transitions in the first overtone of CO absorption in the 2 $\mu$m region (Cushing et al. 2005) and are expected to have a broad fundamental transition feature of CO absorption from 4.3 up to ~5 $\mu$m (Pavlenko & Jones 2002). Brown dwarfs also show a very broad CO absorption at around 4.5 $\mu$m (Yamamura et al. 2010). In the
spectral region of $7–8\,\mu m$, M-type giants have a broad absorption feature of the fundamental transitions of SiO gas (Heras et al. 2002), while M-type dwarfs show no strong features (Cushing et al. 2006). SiO gas absorption could be responsible for part of the observed features at $7–8\,\mu m$ in Object 1 (Figure 6), but SiO gas has much stronger, broad absorption of the first overtone at around $4.2\,\mu m$ in the spectra of M-type giants (Heras et al. 2002), which is not observed in the present spectrum. These expected characteristics do not match with the observed spectra of both objects, suggesting it unlikely that they are background M-type stars.

Both objects are not located in known star-forming regions. Figure 1 indicates that the nearby star-forming activities are located in the southern part of the sky of the two objects, where intense diffuse MIR emission is observed. According to the catalog of the star-forming regions of Avedisova (2002), the nearest star-forming region is IRAS 14004-6104 for Object 1 (6.8′ separation) and IRAS 14004-6104 and RAGL 4188 for Object 2 (both have a 4.2′ separation). The nearest H II region is G311.540+00.319 for both objects and the separations are 5.99′ and 4.22′ for Object 1 and Object 2, respectively (Beuret et al. 2017). Such separations may not be unexpected from the drift motion of YSOs from star-forming regions (Feigelson 1996; Contreras Peña et al. 2014) and the two objects could be runaway YSOs, although the distance to the two objects and their evolutionary stages are not known. An isolated YSO is also reported to be present, which may have been formed in situ (Britt et al. 2016). YSO population not associated with star-forming regions has an impact on the understanding of star-forming activities and history in our galaxy (e.g., de Wit et al. 2005; Renzo et al. 2019). If they are YSOs, the present result suggests that similar objects have eluded past photometric surveys of YSOs (e.g., Gutermuth et al. 2008; Gruendl & Chu 2009; Beemer et al. 2010; Kato et al. 2012; Koenig & Leisawitz 2014). This makes significant implications on the population of YSOs in our galaxy and nearby galaxies. If Object 1 is an MYSO as suggested from the low CO$_2$ ice abundance, it could further make implications on the formation scenario of massive stars, which is not well understood yet, and on the galaxy evolution (e.g., Zinnecker & Yorke 2007; Renzo et al. 2019). Their SEDs may be accounted for by clumpy distribution of absorbing materials around a YSO. Further investigations on modeling are strongly encouraged to understand their nature.

6. Summary

We have discovered two intriguing infrared objects in the AKARI/IRC slitless spectroscopic survey of the Galactic plane. For Object 1, a full spectrum from 2.5–13\,\mu m was successfully extracted, while only a spectrum of 3.1–5\,\mu m was reliably extracted for Object 2 due to the presence of nearby objects and faint nebulousity. Both objects show deep absorption features of H$_2$O, CO$_2$, and CO ices. They also show warm (>100 K) CO gas absorption, suggesting that they are embedded YSOs. The spectrum of Object 1 also indicates strong XCN absorption, further supporting the YSO identification. Other indicators for the thermal processing of ices are also suggested, though they are also compatible with the ice properties seen in background stars. They are not definite evidence for the YSO identification, while there are no indications against it in their spectra.

On the other hand, their SEDs peak at around $5\,\mu m$ and decrease toward longer wavelengths. They are not detected in the HIGAL survey. These characteristics are better reproduced by background stars with large ($A_V \sim 50$) extinction. Both objects are neither located in known star-forming regions nor in known dense clouds. Although the observed SEDs may be explained if the absorbing ice species are located in clumpy concentrations just on the line of sight in the edge-on disk surrounding a YSO, their true nature remains uncertain based on the currently available data.

If they are background stars with large extinction, there must be unknown compact, dense clouds in the lines of sight toward them. The presence and the formation of such isolated dense clouds are not known. If ices are formed in these environments, it will have an impact on the chemical processes in the ISM. If they are truly YSOs, their blue color in the MIR suggests that similar kinds of objects have eluded in past photometric surveys, which have significant implications on our understanding of star formation process and the distribution of star-forming activities in our galaxy and nearby galaxies. It is important to identify true nature of the objects by further observations.

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