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# Ice Features of Low-luminosity Protostars in Near-infrared Spectra of AKARI/IRC

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## Abstract

We present near-infrared spectra of three low-luminosity protostars and one background star in the Perseus molecular cloud, acquired using the infrared camera on board the AKARI space telescope. For the comparison with different star-forming environments, we also present spectra of the massive protostar AFGL 7009S, where the protostellar envelope is heated significantly, and the low-mass protostar RNO 91, which is suspected to be undergoing an episodic burst. We detected ice absorption features of H<sub>2</sub>O, CO<sub>2</sub>, and CO in all spectra around the wavelengths of 3.05, 4.27, and 4.67  $\mu\text{m}$ , respectively. For at least two low-luminosity protostars, we also detected the XCN ice feature at 4.62  $\mu\text{m}$ . The presence of the crystalline H<sub>2</sub>O ice and XCN ice components indicates that the low-luminosity protostars experienced a hot phase via accretion bursts during the past mass accretion process. We compared the ice abundances of the low-luminosity protostars with those of embedded low-mass protostars and the dense molecular clouds and cores, suggesting that their ice abundances reflect the strength of prior bursts and the timescale after the last burst.

*Unified Astronomy Thesaurus concepts:* [Astrochemistry \(75\)](#); [Chemical abundances \(224\)](#); [Interstellar molecules \(849\)](#); [Protostars \(1302\)](#); [Star formation \(1569\)](#); [Spectroscopy \(1558\)](#)

## 1. Introduction

The luminosity function of young stellar objects (YSOs) with a peak luminosity lower than  $1.6 L_{\odot}$  raised questions about the mass accretion process (Evans et al. 2009; Dunham et al. 2010) since their low luminosities cannot be explained well by the standard mass accretion rate of  $\sim 2 \times 10^{-6} M_{\odot} \text{yr}^{-1}$  (Shu et al. 1987). A potential explanation of their low luminosity is the episodic accretion process, which has long-lived quiescent-accretion phases interspersed with short-lived burst-accretion phases (Vorobyov & Basu 2005; Dunham et al. 2010). In this episodic accretion model, some dynamical and chemical conditions, which cannot be explained by the current low luminosity in the continuous accretion model, should exist due to past burst accretions. Therefore, it is interesting to find observational clues supporting the episodic accretion process.

One evidence of episodic accretion can be found in the absorption features of ice spectra. Chemistry in circumstellar envelopes is a useful tracer of the history of the accretion process. Previous studies of low- and high-mass YSOs have suggested that the thermal history of YSOs can be found from the relative distribution of molecular abundances of gas and ice components (Evans et al. 1991; van Dishoeck et al. 1999; Lahuis & van Dishoeck 2000; Boonman & van Dishoeck 2003; Boonman et al. 2003; van Broekhuizen et al. 2005; Lee 2007; Kim et al. 2012; Visser & Bergin 2012). At the early evolutionary stage of YSOs, more molecules reside in the ice

phase on dust grain surfaces rather than in the gas phase (Bergin et al. 1995; Lee et al. 2004).

If low-luminosity objects are in the quiescent phase of an episodic accretion process, those protostars should have gone through a burst-accretion phase in the past with significantly enhanced accretion rates to gain their masses. During the relatively short timescale of burst accretion, the abrupt heating of the surrounding dust grains should sublimate ices from the grain surfaces. When protostars return to a quiescent phase with a low accretion rate, the dust grains cool down to cold conditions similar to those of starless or pre-stellar cores at most radii, where molecules are gradually frozen back onto the grain surfaces as ice (Lee 2007). In particular, significant amounts of oxygen and carbon occupy the main composition of the dust grain mantles, forming H<sub>2</sub>O, CO, and CO<sub>2</sub> ices, which are the known origins of strong absorption features around near- and mid-infrared wavelengths. The memories of hot phases must have been left in these ice features in the episodic accretion process, although the current low luminosity implies only a cold condition.

The ice formation and evolution on the grain surfaces are linked with the thermal process of mixed ices in the mantles. In previous CO ice studies, it was noted that H<sub>2</sub>O and CO can form mixed layers (Collings et al. 2003; Pontoppidan et al. 2003). Gas-phase CO molecules are frozen as CO ice during the quiescent phase, and some of them turn into CO<sub>2</sub> ice (Kim et al. 2011, 2012). A pure component of CO<sub>2</sub> ice can be formed by the distillation process, in which CO evaporates from a CO–CO<sub>2</sub> mixture, leaving CO<sub>2</sub> ice in the stable phase due to lower thermal conditions ( $\sim 20$ – $30$  K) within the protostellar envelope (Pontoppidan et al. 2008). In the episodic accretion process, if an accretion burst occurs and the temperature at some radii reaches conditions favoring the sublimation of CO



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**Table 1**  
Photometric Information

Source Name	Position		Fluxes (mJy)								$L_{\text{bol}}^a$ ( $L_{\odot}$ )	$T_{\text{bol}}^a$ (K)	
	$\alpha_{J2000.0}$	$\delta_{J2000.0}$	2MASS			IRAC Band				MIPS Band			
			$J$	$H$	$K$	1	2	3	4	1			2
Perseus 1	3 26 37.46	30 15 28.1	0.18	0.50	1.19	3.62	9.27	11.1	12.0	396	4300	1.10 (0.69 <sup>b</sup> )	64
Perseus 2	3 32 29.18	31 02 40.9	0.71	2.69	5.81	11.1	17.2	23.3	32.8	181	1130	0.57 (0.20 <sup>b</sup> )	114
Perseus 3	3 43 51.02	32 03 07.9	...	...	...	6.81	3.99	12.8	2.15	45.4	1960	0.32 (0.33 <sup>b</sup> )	63
J03293654+3129465	3 29 36.54	31 29 45.5	13.4	76.6	130	102	69.8	53.6	29.9	3.75	...	...	...
RNO 91	16 34 29.32	-15 47 01.4	63.8	143	274	737	1110	1440	1660	5000	20300	2.6 <sup>c</sup>	340 <sup>c</sup>
AFGL 7009S	18 34 20.91	-5 59 42.2	0.13	0.50	9.00	...	...	...	...	...	...	$2.9 \times 10^{4d}$	...

**Notes.**

<sup>a</sup>  $L_{\text{bol}}$  and  $T_{\text{bol}}$  are referred from Dunham et al. (2008), excepting for RNO 91 and AFGL 7009S.

<sup>b</sup> Internal luminosity ( $L_{\text{int}}$ ) of the central protostar.  $L_{\text{int}}$  is derived from 70  $\mu\text{m}$  flux (Dunham et al. 2008).

<sup>c</sup> Lee et al. (2015b).

<sup>d</sup> Zapata et al. (2009).

ice, the CO will evaporate from the mixed-ice grains, leaving behind pure CO<sub>2</sub> ice. As a result, in a quiescent phase with a low luminosity after a burst accretion stops, pure CO<sub>2</sub> ice will be detectable.

Observations of the absorption features of these ice components have been conducted with infrared space telescopes that are sensitive enough to detect weak absorption features, even in the spectra of low-luminosity objects, without any atmospheric interference. Spitzer IRS spectra of CO<sub>2</sub> ice at 15.2  $\mu\text{m}$  toward low-luminosity objects show a double-peaked feature, which is direct evidence of pure CO<sub>2</sub> ice (Kim et al. 2012). The double-peaked feature of CO<sub>2</sub> ice indicates that the low-luminosity protostellar system must have had periods of hot phases. The absorption features of the most abundant ices (H<sub>2</sub>O, CO<sub>2</sub>, and CO) have been also observed by the Infrared Camera (IRC) on board the AKARI space telescope in the near-infrared range (2.5–5.0  $\mu\text{m}$ ). This near-infrared range also covers the 4.62  $\mu\text{m}$  XCN feature (Gibb et al. 2004), which is an important tracer of thermal history in circumstellar material.

In this paper, we study the ice abundances of low-luminosity protostellar envelopes as well as the natal cloud in the Perseus star-forming region, using spectroscopic observations obtained with the AKARI space telescope. For the comparison of ice abundances between the low-luminosity sources and typical embedded low- and high-mass YSOs, we also examine the near-infrared spectra of RNO 91 and AFGL 7009S, which were covered as part of our ice survey. From the spectral analysis of the detected ice absorption features, including the XCN ice, we explore the chemical differences in the ices of the embedded low-mass YSOs, molecular clouds, and low-luminosity protostars. In Section 2, our targets, including low-luminosity sources and two other protostars, are described. We explain the data reduction pipeline in Section 3. In Section 4, we describe the procedure used to extract the ice features from the AKARI IRC spectra and derive their optical depth profiles and column densities. In Section 5, we discuss the XCN ice feature detected in our low-luminosity targets as a direct evidence of a past enhanced luminosity phase due to an accretion burst. Different distributions of the ice abundances in various evolutionary stages of star formation, resulting from the surface chemistry

during the different timescales after the burst ends, are also discussed.

## 2. Observations

### 2.1. Targets in the Perseus Molecular Cloud

Observations of three low-luminosity protostars and one background star in the Perseus region were carried out as part of the AKARI Phase-3 (post-helium mission) open time program “ices in Star Forming CorEs” (SFICE; PI: Jeong-Eun Lee), which observed 16 sources covering known YSOs and background stars to study the physical and chemical properties at various evolutionary stages of low-mass star formation.

Our main targets for this study are three embedded protostellar objects with internal luminosities ( $L_{\text{int}}$ ) lower than 1  $L_{\odot}$  discovered by Dunham et al. (2008). The identification numbers of those targets, as given by Dunham et al. (2008), are 060, 090, and 104, but for this work, we label them Perseus 1, 2, and 3, respectively, because all three sources are located in the Perseus molecular cloud. The  $L_{\text{int}}$  of the central protostar was determined from the flux at 70  $\mu\text{m}$  (Dunham et al. 2008). We have listed the source information in Table 1, including the flux at infrared wavelengths (Evans et al. 2003; Skrutskie et al. 2006), the luminosity derived from the 70  $\mu\text{m}$  flux, and the bolometric temperature.

Environmental effects, such as the external radiation field and the cloud’s initial density, temperature, and chemical conditions could be ignored because all the sources are located in the same molecular cloud. A background star behind the Perseus molecular cloud was also included in our program to study the chemical evolution of circumstellar material around low-luminosity protostars from their nascent condition. The ice composition of a molecular cloud can be studied via absorption features against a background infrared continuum source. The background source used in this work is a K-type giant, and its fluxes at infrared wavelengths have been calculated from 2MASS and Spitzer observations (Evans et al. 2003; Skrutskie et al. 2006).

## 2.2. Targets for Comparisons: RNO 91 and AFGL 7009S

RNO 91 and AFGL 7009S are normal low- and high-mass protostars, respectively, and spectroscopic studies of them have been carried out in the mid-infrared wavelength range. We use these two protostars for comparisons with our low-luminosity targets from the view of chemical evolution.

RNO 91 (also known as IRAS 16316-1540) is known as a Class I protostar (Chen et al. 2009) embedded in a reflection nebula (Mayama et al. 2007), located in the Ophiuchus molecular cloud. It was recently observed as part of the protoplanetary disk survey with the Immersion Grating Infrared Spectrograph (IGRINS) in the near-infrared *H* and *K* bands (Yoon et al. 2021). The IGRINS spectra of RNO 91 show broad absorption features in the CO overtone bands, water vapor bands, and various atomic lines, which are similar to the spectral characteristics of FU Orionis objects (Lee et al. 2015a; Park et al. 2020). In addition, they show the double-peaked pure CO ice feature at  $15\ \mu\text{m}$  (Pontoppidan et al. 2008). Therefore, these features strongly suggest that RNO 91 is undergoing an accretion burst with an enhanced mass accretion rate in spite of its normal luminosity. On the other hand, the low-luminosity sources are considered to be in a quiescent phase with low accretion rates (Dunham et al. 2010). In the episodic accretion model, all protostars even with current low luminosities must have undergone burst accretions. In addition, the chemical compositions affected by the burst accretions remain much longer than the dynamical timescale of burst accretion (Lee 2007). Therefore, comparisons of the ice compositions between RNO 91 and the low-luminosity sources will provide an important opportunity to investigate the chemical evolution in the episodic accretion model.

AFGL 7009S (also known as IRAS 18316-0602) is one of the most massive Class I YSOs studied to date (Gibb et al. 2004). It has been observed with the Infrared Space Observatory (ISO) Short and Long Wavelengths Spectrometers (SWS and LWS), and numerous studies for this target have been carried out (d’Hendecourt et al. 1996; Dartois et al. 1998, 2000; Gibb et al. 2004). This object has saturated absorption features of  $\text{H}_2\text{O}$  and  $\text{CO}_2$  ices throughout 3 and  $4.27\ \mu\text{m}$ , as observed with the ISO. The  $\text{H}_2\text{O}$  column density was estimated by d’Hendecourt et al. (1996) using both the 6 and  $13\ \mu\text{m}$  features. Our near-infrared spectroscopic data for AFGL 7009S can provide a comparison of the ice chemistry between low- and high-mass star formation in the deeply embedded stage.

## 2.3. Observations with AKARI IRC

We performed near-infrared spectroscopic observations of our targets using AKARI IRC on 2009 February 15 and 17, August 21 and 23, September 2, and October 1. We used the IRC grism (NG) mode, which covers  $2.5\text{--}5.0\ \mu\text{m}$  with a spectral resolution of  $R \sim 100$  at  $3.6\ \mu\text{m}$  (Onaka et al. 2007). This resolving power was taken from the dispersion rate per pixel ( $1''.46$ ) of  $0.0097\ \mu\text{m}$  (Ohya et al. 2007) at the focal plane, and such a resolution range has been guaranteed to detect the ice absorption bands (Aikawa et al. 2012; Noble et al. 2013). We adopted the standard point source spectroscopic (Np) mode, which provides a  $1' \times 1'$  slit aperture to minimize light contamination by nearby bright sources. From the standard spectroscopic observing sequence, we obtained seven spectroscopic frames and one imaging frame (reference

image) in the middle of them. Each frame consists of a short exposure (4 s) and a long exposure (44 s). Combining the spectroscopic frames, the total integration time was 400 s. Figure 1(a) shows the imaging frames of our targets.

## 3. Data Reduction

A data reduction process was performed through the spectroscopy pipeline for AKARI IRC phase 3 (Ohya et al. 2007; Onaka et al. 2007). This pipeline was provided by the AKARI project team, and we used its latest version of the toolkit, IRC\_SPECRED, based on the IDL environment. For dark subtraction from the raw data, five self-dark images were taken at the preceding and subsequent frames of the data archive. We applied a linearity correction and saturation masking by comparing the reference images between short and long exposure frames. A flat-fielding process was not included during the data reduction due to poor signal-to-noise ratios of a flat image of NG spectra in the Np mode. Subtraction of the sky values was also performed using the dark-subtracted image.

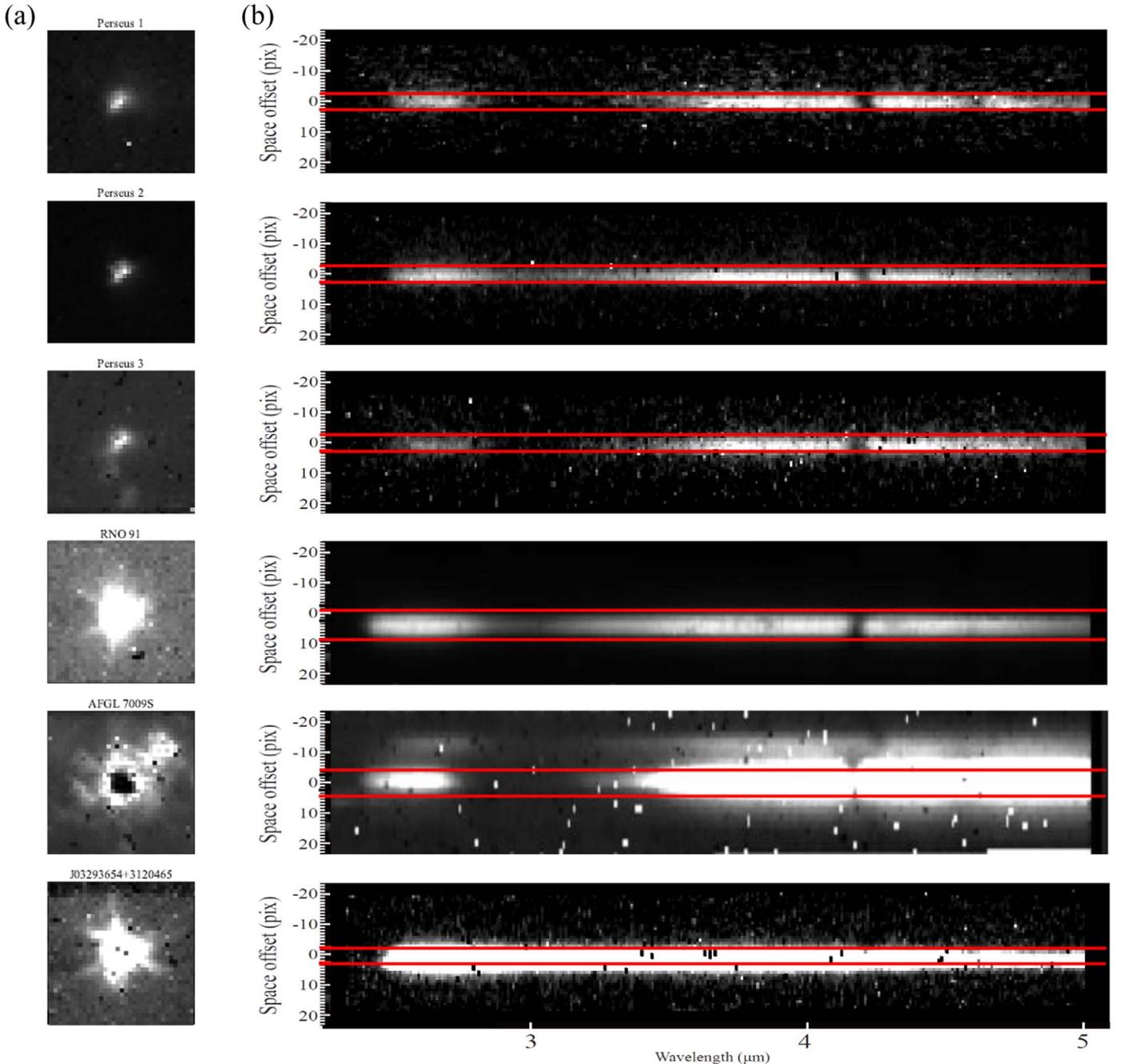
The source detection of the reference image was executed through the IRAF “DAOFIND” task automatically or manually, by inserting source coordinates into the pipeline command.<sup>7</sup> Based on the source coordinates found in the reference image before stacking into a final spectral image, the eight spectral images were shifted by the attitude drift of the AKARI satellite. After subtracting cosmic rays and the remaining background signals, the spectral images were stacked and averaged with a wavelength calibration for the reference image and the extracted spectrum. The signal was integrated over five pixels along with the spatial direction. Figure 1(b) shows the spectral images at each target. The stellar light was dispersed from left (short wavelengths) to right (long wavelengths). The spectrum was not perfectly aligned with the rows of pixels, and we adopted the correction formula to tilt the spectrum as indicated below,

$$Y = -0.00746929(X - X_0) + Y_0, \quad (1)$$

where  $X$  and  $Y$  are the pixel numbers in the dispersion direction and spatial direction, respectively, and  $X_0$  and  $Y_0$  indicate the center of the spectrum.

Finally, the integrated signal was corrected using a spectral response function before being converted into a spectrum. The response function in the previous version of the toolkit was based on calibrated observations of blue standard stars, which suffered from severe 2nd-order light contamination (Baba et al. 2016). In the current version of the toolkit, the response function corrects the effect of contamination on the part considered. The flux error was estimated using the noise level in the sky region and the response function. According to Aikawa et al. (2012), the linear correlation between pixel and wavelength is less certain at longer wavelengths. Therefore, we shifted the spectral data by 1–2 pixels using the task CHANGE\_WAVE\_OFFSET, to fit the pixel position and spectral wavelengths.

<sup>7</sup> IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.



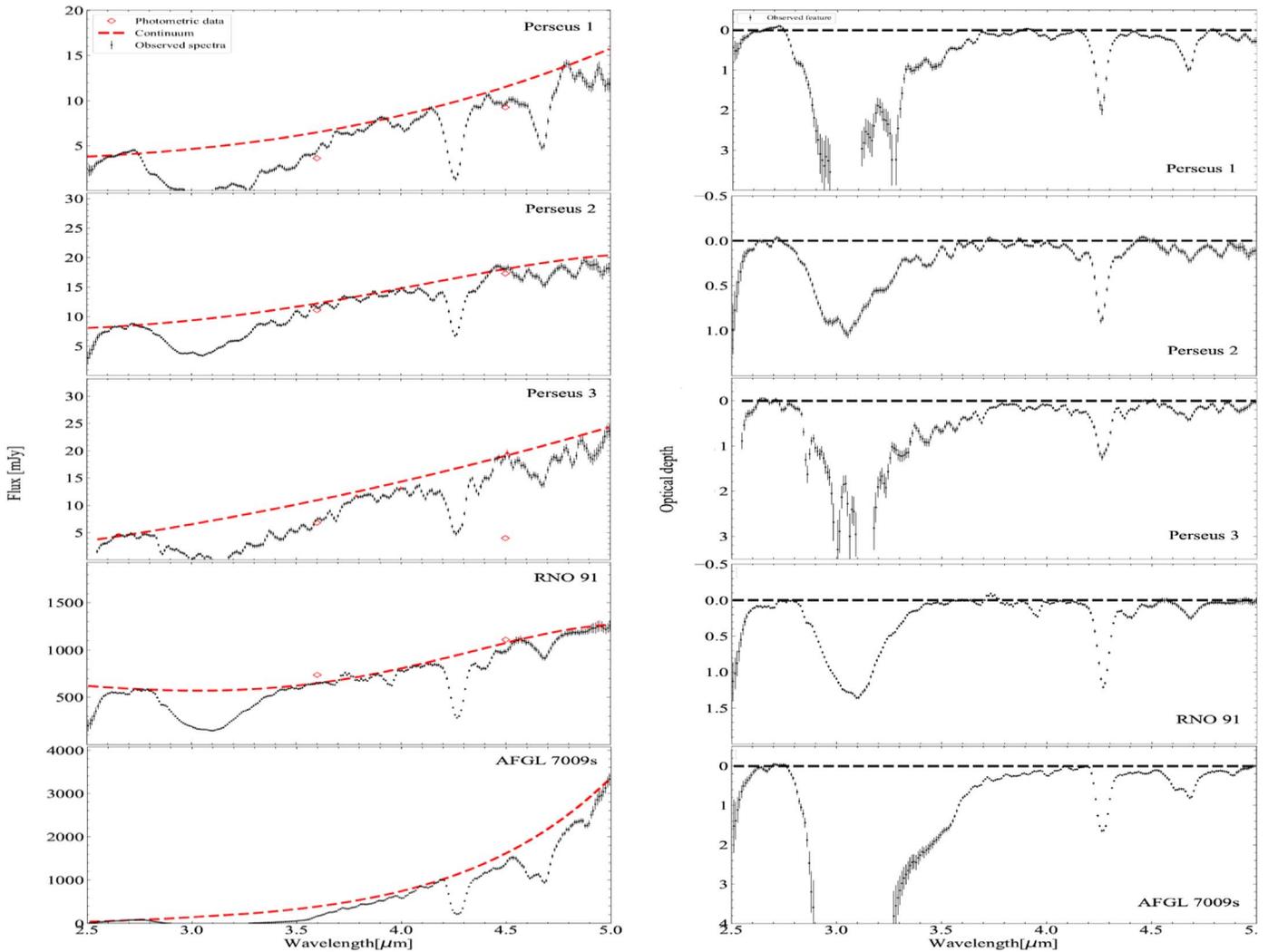
**Figure 1.** (a) Images of our targets with the N3 filter with a  $1' \times 1'$  field of view. The coordinate at the center of each image is listed in Table 1. (b) Spectral images of our targets, obtained from the spectroscopic pipeline process. The dispersion direction is left to right. The red lines indicate the pixel range of spatial integration.

## 4. Results

### 4.1. Reduced Spectra

In Figure 2, the reduced AKARI IRC spectra of all protostars are presented; the absorption features of the  $\text{H}_2\text{O}$ ,  $\text{CO}_2$ , and CO ices are clearly detected. All of our targets show deep and broad absorption features of  $\text{H}_2\text{O}$  ice in the wavelength range  $2.7\text{--}3.4 \mu\text{m}$ . In the case of AFGL 7009S, strong extinction toward the source saturates the absorption features throughout the wavelengths from  $2.7$  to  $3.6 \mu\text{m}$ , including  $\text{H}_2\text{O}$  ice. Other ice features, such as  $\text{CH}_4$  (Lacy et al. 1991; Boogert et al. 2004) and  $\text{CH}_3\text{OH}$  (Grim et al. 1991; Brooke et al. 1996), were observed at  $3.3\text{--}3.5 \mu\text{m}$ , but it is difficult to extract their

absorption profiles from the blended features due to the low spectral resolution of AKARI IRC. An absorption feature of the  $\text{CO}_2$  ice around  $4.27 \mu\text{m}$  was clearly detected toward all targets. At the wavelength around  $4.6 \mu\text{m}$  for Perseus 1 and 3, RNO 91, and AFGL 7009S, there is a hint for another ice component overlapping with the CO absorption feature at  $4.67 \mu\text{m}$ . Many near-infrared observations have revealed the same feature on the blue wing part of the CO absorption feature (Tegler et al. 1995; Chiar et al. 1998; Whittet et al. 2001; van Broekhuizen et al. 2005; Aikawa et al. 2012), which was suggested as an absorption feature of XCN ice. Lacy et al. (1984) and Pendleton et al. (1999) reported that the  $4.62 \mu\text{m}$  absorption feature of XCN ice consists of a nitrile group and an unknown



**Figure 2.** The observed AKARI IRC spectra (left) and the corresponding optical depth plot (right) for all the sources in this study, except the background star J03293654+3129465 (See Figure 3). The red dashed line shows the continuum determined by second- to third-order polynomial fitting of the spectrum. The opened red diamonds are the Spitzer IRAC 3.6 and 4.5  $\mu\text{m}$  fluxes, which are referred from the C2D YSO catalog (Evans et al. 2003). The optical depth is calculated from the equation,  $\tau = \ln(I_0/I)$ , where  $I_0$  and  $I$  are the continuum and observed fluxes, respectively.

component “X”. Many laboratory studies have suggested that UV photolysis or cosmic ray irradiation of ice mantle could make the solid state  $\text{OCN}^-$  on grain surfaces (Lacy et al. 1984; Grim & Greenberg 1987; Bernstein et al. 2000; Palumbo et al. 2000; Hudson et al. 2001; van Broekhuizen et al. 2004). In addition to these ice components, there are some absorption features around 4.8 and 4.9  $\mu\text{m}$ . For Perseus 3 and the background star, the absorption features with a peak position around 4.78  $\mu\text{m}$  are likely associated with  $^{13}\text{CO}$  ice (Boogert et al. 2002; Pontoppidan et al. 2003). We also detected another absorption feature at 4.83  $\mu\text{m}$  toward the low-luminosity targets. However, we could not find any corresponding ice features from previous studies. The 4.9  $\mu\text{m}$  absorption feature detected toward all targets was identified as solid carbonyl sulfide (OCS) ice. OCS ice can be produced when the interstellar ices containing CO and  $\text{CO}_2$  are exposed to UV photons or cosmic rays (Palumbo et al. 1997).

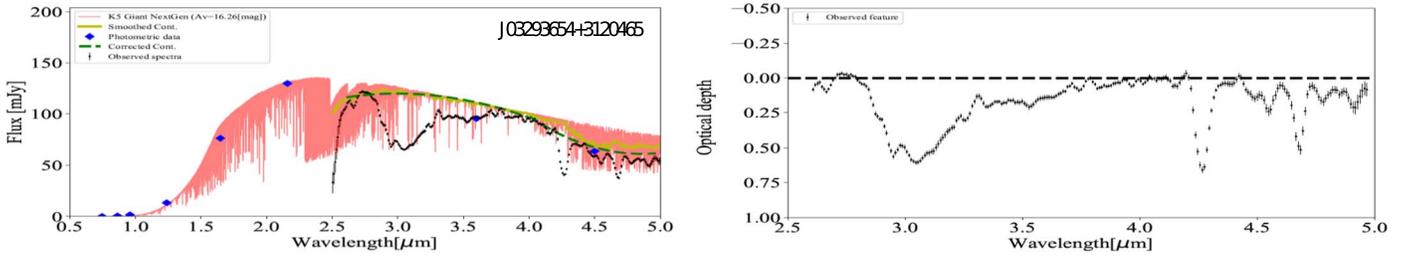
#### 4.2. Analyses of the Ice Absorption Features

In order to quantify the ice abundances from the absorption features, we needed to derive the column density ( $N$ ) of each

ice component, which were obtained using the following equation,

$$N = \frac{\int \tau d\nu}{A}, \quad (2)$$

where  $A$  is the band strength (in  $\text{cm molecule}^{-1}$ ) and  $\tau$  is the optical depth. The band strengths of  $\text{H}_2\text{O}$ ,  $\text{CO}_2$ , and CO are  $2.0 \times 10^{-16}$ ,  $7.6 \times 10^{-17}$ , and  $1.1 \times 10^{-17}$   $\text{cm molecule}^{-1}$ , respectively (Gerakines et al. 1995). We determined the optical depth of each spectrum through the normalized flux using the continuum, which was interpolated with a polynomial function (Boogert et al. 2008; Pontoppidan et al. 2008). It was not easy to select continuum points to be used as pristine continuum levels because there are numerous absorption and emission bands in our spectral window. We used second- to third-order polynomial functions to fit the continuum using five wavelength ranges: 2.6–2.8, 3.4–3.7, 4.1–4.2, 4.4–4.6, and 4.7–4.9  $\mu\text{m}$ . Those fitting ranges were set to avoid absorption features, varying slightly for each object to optimize the



**Figure 3.** The same plots as Figure 2, but for the background star behind the Perseus molecular cloud. The green dashed line shows the corrected continuum determined by the reddened (red line) and smoothed NextGen model data (gold line) and 2MASS data points (blue squares).

continuum levels of each spectrum. The optimized continuum for each target is overlaid as a dashed curve in Figure 2.

In the case of the background star, a different method was employed to determine the optical depth of its spectral data. We adopted a NextGen stellar model as the continuum of the background star, a K5 giant, to remove the effect of the absorption feature in the intrinsic stellar spectrum. Foreground dust extinction ( $A_V$ ) of the background star was estimated using a color-color diagram from the 2MASS photometric data (Cutri et al. 2003). According to the opacity and reddening vector of 2.078 (Weingartner & Draine 2001), we derived  $A_V$  (16.25 mag) and applied it to the model data. The reddened model data were fitted to our spectrum and then were smoothed to the spectral resolution of AKARI IRC. For the case of wavelengths shorter than  $3.7 \mu\text{m}$ , we extrapolated the smoothed model data with the 2MASS data points, due to the contamination by the broad absorption feature around  $3.0 \mu\text{m}$ . At longer wavelengths, we used a third-order polynomial function to fit the continuum levels. Finally, the continuum data were produced by interpolating them. Figure 3 shows the corrected continuum curve and smoothed NextGen model data on top of the spectrum of the background star.

Derivation of the intrinsic optical depth profile for each ice component is conducted via the fitting of experimental ice absorbance data to the observed spectra. We used the experimental data of Ehrenfreund et al. (1996), Gerakines et al. (1995), and Fraser & van Dishoeck (2004) to fit our spectra and calculate the ice column densities. However, in the near-infrared range ( $2.5\text{--}5.0 \mu\text{m}$ ), the grain shape and size can affect the shape and peak position of the ice absorption features (Ehrenfreund et al. 1997; Noble et al. 2013). For the experimental data of the  $\text{CO}_2$  and  $\text{CO}$  ice components, we adopted the continuously distributed ellipsoids (CDE) grain model to correct their absorbance profiles because the absorption wavelengths are similar to the sizes of the grains (Ehrenfreund et al. 1997; Pontoppidan et al. 2003). After the grain shape correction, given the low spectral resolution of IRC, we convolved the experimental data with the AKARI IRC instrumental line profile resulting from the point-spread function (PSF) of the detector, and then re-binned it to AKARI’s resolving power. The experimental data are divided into polar and apolar ices, and thus, we used combinations of polar and apolar mixtures to fit those observed absorption features by weighting the ice abundances uniformly at all wavelengths. The best-fit experimental profiles are listed in Table 2.

Figure 4 shows the best-fit results for the absorption features of  $\text{H}_2\text{O}$  ice. We used the wavelength range  $2.78\text{--}2.95 \mu\text{m}$  to evaluate the goodness of fit of the  $\text{H}_2\text{O}$  absorption features, first. We avoided the central data points of the  $\text{H}_2\text{O}$  ice

absorption from the experimental profile because half of our targets are affected significantly by saturation (see Perseus 1, Perseus 3, and AFGL 7009S). The absorption features of the protostars were fitted by a mixture of amorphous and crystalline pure  $\text{H}_2\text{O}$  ices at 10 K and 160 K, respectively. The crystalline ice component, which has a sharp absorption feature at  $3.1 \mu\text{m}$ , is linked to the thermal processing of ice (Boogert et al. 2015). In the case of low-luminosity protostars, the existence of the crystalline ice component may support the idea that they have experienced higher luminosities that induced the crystallization of amorphous  $\text{H}_2\text{O}$  ice. Interestingly, the  $\text{H}_2\text{O}$  absorption feature toward Perseus 3 was fitted mostly by the crystalline ice component, while Perseus 1 was fitted mostly by the amorphous component.

Together with the water ice, we also considered a polar ice mixture of  $\text{H}_2\text{O}:\text{NH}_3 = 100:20$  at 10 K to fit the absorption by the  $\text{NH}_3$  ice at  $2.98 \mu\text{m}$  detected for Perseus 2 and the background star.  $\text{NH}_3$  absorption features were previously detected at  $2.98$  (pure; Aikawa et al. 2012) or  $3.47$  (hydrate; Dartois et al. 2002)  $\mu\text{m}$ . Although the absorption spectra of Perseus 2 and the background star show a double-peaked profile at the central part, the peak positions, and therefore, their origins are different; for Perseus 2, the peak is located at  $3.10 \mu\text{m}$ , and thus, produced by the crystalline  $\text{H}_2\text{O}$  ice component, while for the background star, the absorption peak appears at  $3.05 \mu\text{m}$ , indicative of the amorphous  $\text{H}_2\text{O}$  ice component. Therefore, we fitted the ice feature of the background star using a combination of the amorphous and the  $\text{NH}_3$ -mixed profiles at 10 K. For AFGL 7009S, we applied a higher temperature of 50 K to the amorphous ice profile, according to a previous study of the same target (Gibb et al. 2004). We fitted the absorption feature of AFGL 7009S by adopting the results of Gibb et al. (2004) because it was challenging to evaluate the goodness of fit due to the extremely saturated  $\text{H}_2\text{O}$  absorption.

The stretching mode of  $\text{CO}_2$  at  $4.27 \mu\text{m}$  shows a clear and deep absorption feature toward our targets. This deep absorption feature can be easily saturated (Noble et al. 2013), and thus, we avoided the central four data points and employed both side wings of the  $\text{CO}_2$  absorption feature to fit the experimental profiles; the fitted profiles result in a little deeper central feature compared to the observed one. We first adopted the same ice components as applied to the  $15 \mu\text{m}$  bending mode of  $\text{CO}_2$  ice (Pontoppidan et al. 2008; Kim et al. 2012), but it was difficult to decompose each ice component from the observed ice feature of the  $\text{CO}_2$  stretching mode probably due to the spectral resolution of AKARI. As a result, we used only three components from the profiles:  $\text{H}_2\text{O}$ -rich and  $\text{CO}$ -rich ice mixtures and pure  $\text{CO}_2$  ice. We fitted the  $\text{CO}_2$  absorption feature of Perseus 1 with the  $\text{H}_2\text{O}$ -rich ( $\text{H}_2\text{O}:\text{CO}_2 = 100:14$ )

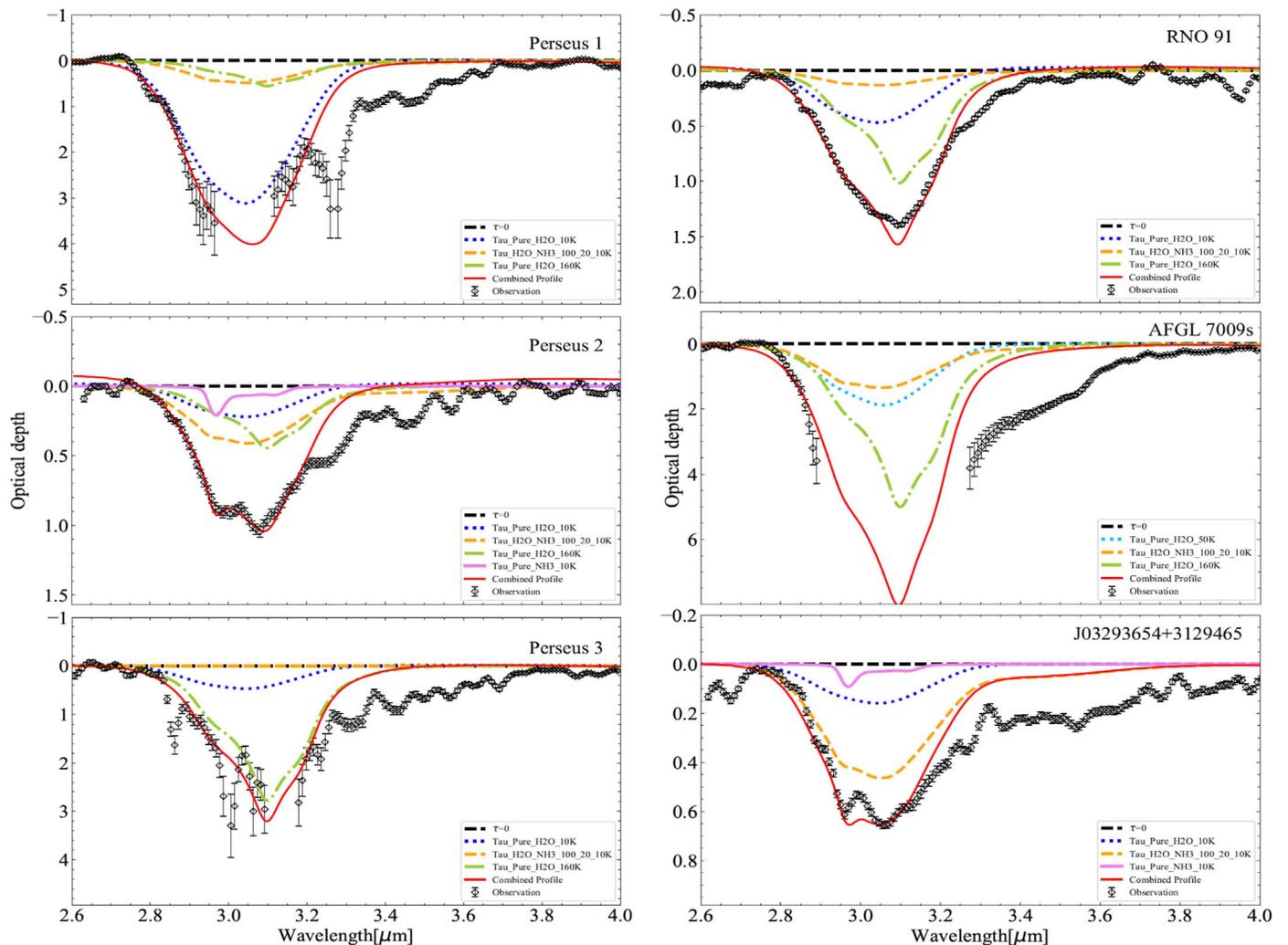
**Table 2**  
Best-fitting Laboratory Data<sup>a</sup>

Source Name	Polar Component	Apolar Component	Pure Component <sup>b</sup>
Perseus 1	H <sub>2</sub> O:NH <sub>3</sub> = 100:20 H <sub>2</sub> O:CO <sub>2</sub> = 100:14 H <sub>2</sub> O:CO = 100:20	CO:CO <sub>2</sub> = 100:70	H <sub>2</sub> O, CO <sub>2</sub>
Perseus 2	H <sub>2</sub> O:NH <sub>3</sub> = 100:20 H <sub>2</sub> O:CO = 100:20	CO:CO <sub>2</sub> = 100:70 H <sub>2</sub> O:CO <sub>2</sub> = 1:6	H <sub>2</sub> O, CO <sub>2</sub>
Perseus 3	H <sub>2</sub> O:CO = 100:10	CO:CO <sub>2</sub> = 100:70 H <sub>2</sub> O:CO <sub>2</sub> = 1:6	H <sub>2</sub> O, CO <sub>2</sub>
J03293654+3129465	H <sub>2</sub> O:NH <sub>3</sub> = 100:20 H <sub>2</sub> O:CO = 100:20	H <sub>2</sub> O:CO <sub>2</sub> = 1:6 CO:CO <sub>2</sub> = 1:1 at 15 K	H <sub>2</sub> O
RNO 91	H <sub>2</sub> O:NH <sub>3</sub> = 100:20 H <sub>2</sub> O:CO = 100:20	H <sub>2</sub> O:CO <sub>2</sub> = 1:6 CO:CO <sub>2</sub> = 100:70	H <sub>2</sub> O, CO <sub>2</sub>
AFGL 7009S	H <sub>2</sub> O:NH <sub>3</sub> = 100:20 H <sub>2</sub> O:CO <sub>2</sub> :CO = 100:20:3 at 20 K	H <sub>2</sub> O:CO <sub>2</sub> = 1:6 H <sub>2</sub> O:CO:O <sub>2</sub> = 1:20:60 at 30 K H <sub>2</sub> O:CH <sub>3</sub> OH:CO <sub>2</sub> = 1:1:1 at 112 K	H <sub>2</sub> O

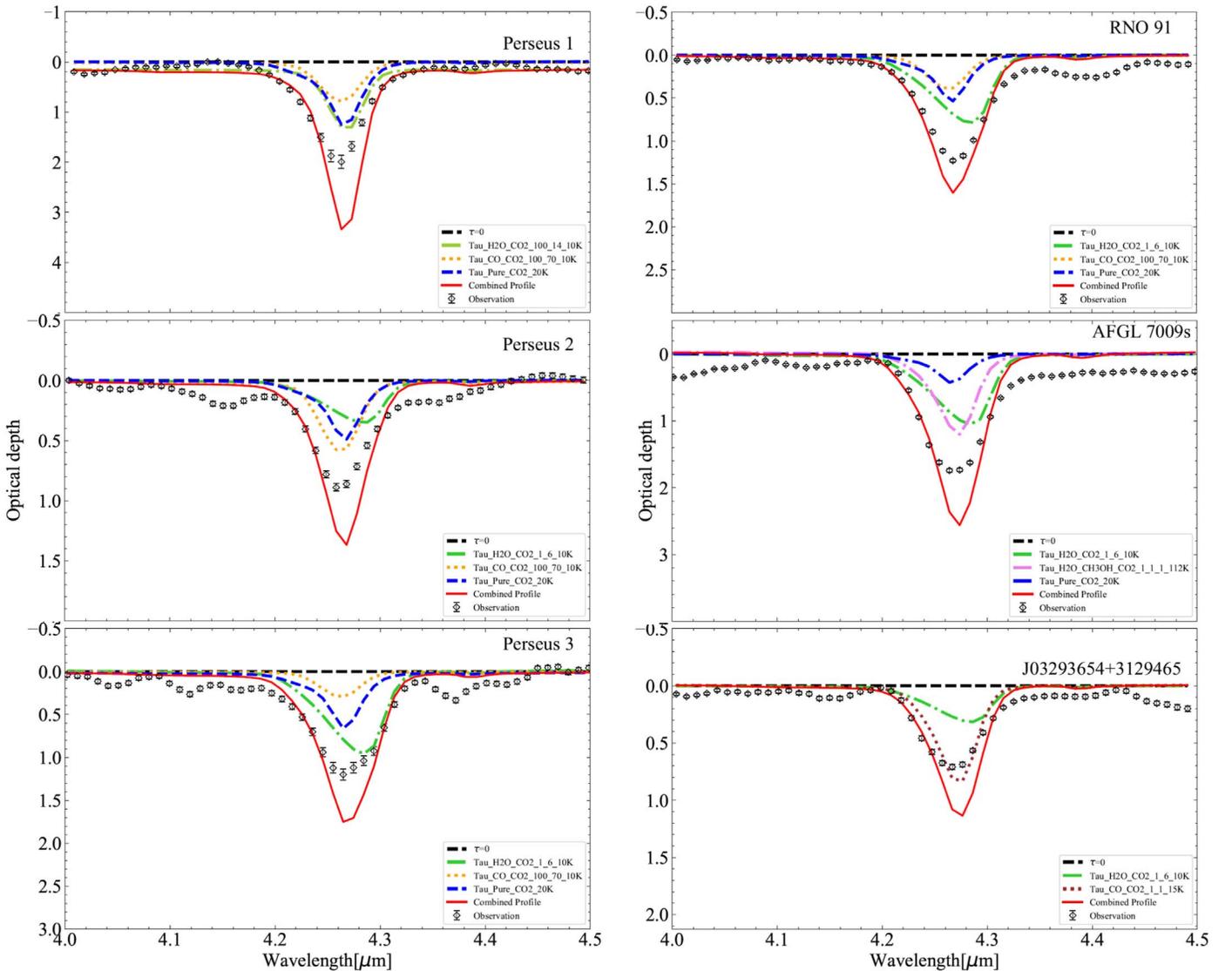
**Notes.**

<sup>a</sup> All ice mixtures are the results of experiments at 10 K except for the cases of AFGL 7009S and J03293654+3129465.

<sup>b</sup> Pure H<sub>2</sub>O ices are divided into amorphous (10 K) and crystalline (160 K) components except for the cases of AFGL 7009S (amorphous component at 50 K only) and J03293654+3129465 (amorphous component at 10 K only). All pure CO<sub>2</sub> profiles are the results of experiments at 20 K.



**Figure 4.** The best-fit results of the H<sub>2</sub>O ice absorption feature for all the sources in this study. Black diamonds present the derived data points of the optical depth with error bars. Some water ice features are saturated (Perseus 1 and 3 and AFGL 7009S). The fitted laboratory profiles are described in the bottom right of each panel. The combined ice profile with the pure amorphous (blue or cyan dotted lines) and crystalline (green dotted-dashed line) components and polar mixture (orange dashed line) is described as the red solid line. The pure NH<sub>3</sub> ice profile (magenta) is applied to fit the double-peaked features of Perseus 2 and the background star.

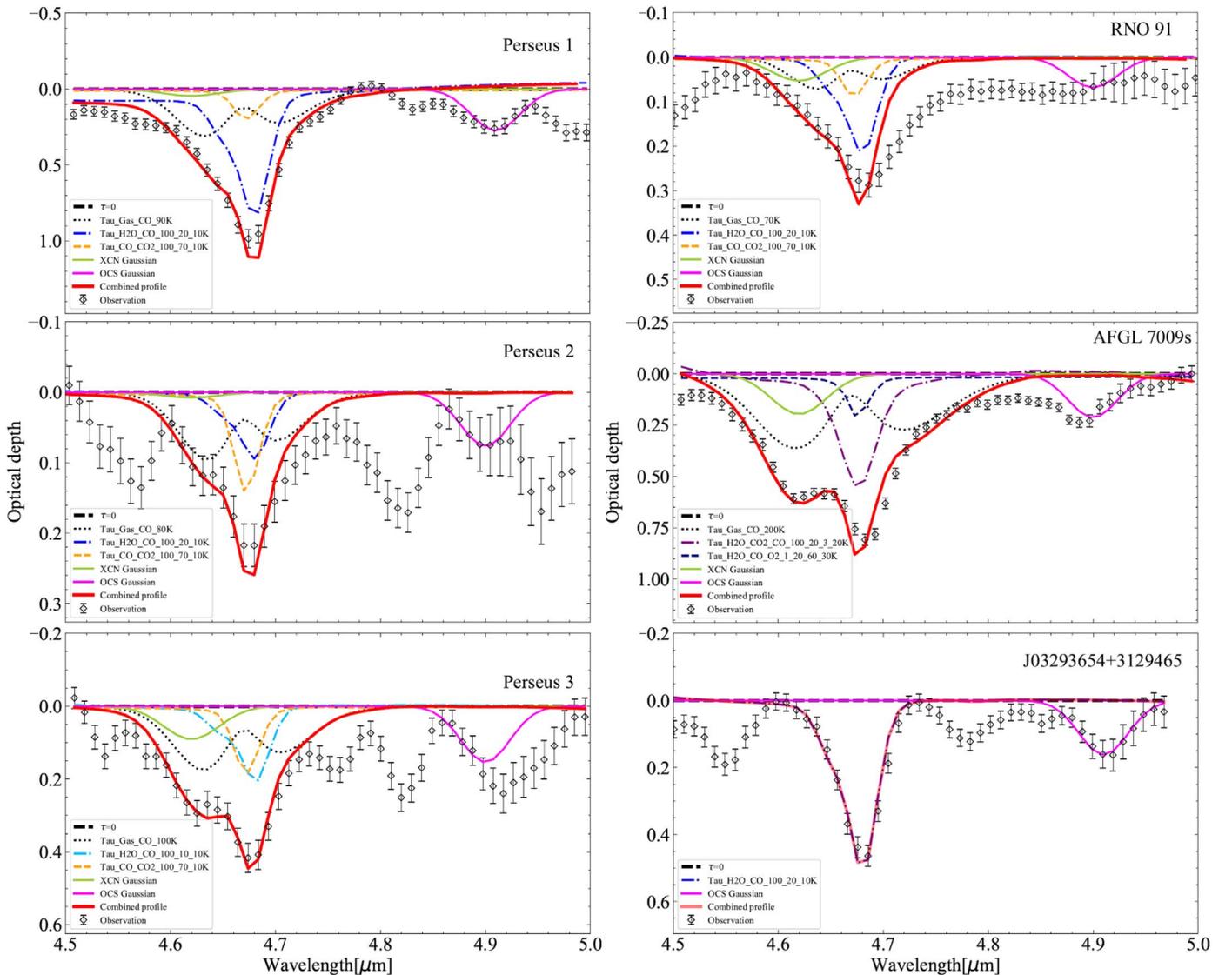


**Figure 5.** The best-fit results of the CO<sub>2</sub> ice absorption feature for all the sources in this study. The pure CO<sub>2</sub> ice profile at 20 K is applied to fit each ice absorption feature, except those of the background star. The fitted laboratory profiles are described in the bottom right of each panel. The combined ice profile with the pure (blue dashed line), H<sub>2</sub>O-mixed (green dotted-dashed line), and CO-mixed (orange dotted line) components is described as the red solid line. We fit the absorption feature of AFGL 7009S to the laboratory ice profile for a massive protostar (Gibb et al. 2004). A brown dotted line for the background star denotes an apolar mixture of CO:CO<sub>2</sub> = 1:1 at 15 K.

and CO-rich (CO:CO<sub>2</sub> = 100:70) ice mixtures, adopting the column density ratio of those ice mixtures derived by Kim et al. (2012). The apolar mixture of H<sub>2</sub>O:CO<sub>2</sub> = 1:6 at 10 K was applied to fit the CO<sub>2</sub> absorption features of other targets. We set a different apolar mixture to fit the CO<sub>2</sub> absorption feature of the background star, following Noble et al. (2013). For AFGL 7009S, we adopted the experimental profile of H<sub>2</sub>O:CH<sub>3</sub>OH:CO<sub>2</sub> = 1:1:1 at 112 K, which was used to fit the CO<sub>2</sub> absorption feature for massive protostars (Gibb et al. 2004). In the quiescent phase after a burst accretion stops, some CO<sub>2</sub> ice is left in pure form after CO evaporates from the CO<sub>2</sub>–CO ice mixture, as presented by Kim et al. (2012) using Spitzer/IRS spectra. For our low-luminosity targets, we used the pure component of CO<sub>2</sub> ice at 20 K (Kim et al. 2012). Figure 5 shows the best-fit results for the CO<sub>2</sub> ice absorption features.

The absorption features of CO ice toward the protostars generally show a broad wing structure, which is likely

overlapped with other ice and gas components. The blue wing is probably combined with the XCN ice feature and absorption lines of the gas-phase CO (*R* branch). The red wing also corresponds to the *P* branch of the CO gas absorption lines which broaden due to the low spectral resolution of AKARI IRC. The gas absorption feature of CO at warm temperatures (>70 K; Mitchell et al. 1990) has been reported for embedded protostars (Whittet & Tielens 1997; Aikawa et al. 2012; Onaka et al. 2021). Therefore, detection of the warm CO gas component, along with the crystalline component of the H<sub>2</sub>O ice, is considered a strong signature of heating by the central protostar (Onaka et al. 2021). We fitted the XCN ice with a Gaussian profile, but the CO gas absorption feature was fitted with the gas model profile. The gas temperatures of the fitted CO gas are in the range of 80 to 100 K for the low-luminosity sources, suggesting that their envelopes had a high thermal condition in the recent past. In the case of AFGL 7009S, we applied the absorption profile corresponding to a CO gas



**Figure 6.** The best-fit results of the CO, XCN, and OCS ice absorption features for all the sources in this study. The polar ice (dotted–dashed line) and apolar ice mixtures (orange dashed line) at 10 K compose the CO ice features, except for AFGL 7009S. We fit the absorption feature of AFGL 7009S with the laboratory ice profile for a massive protostar (Gibb et al. 2004). The solid green and magenta lines show the Gaussian profiles for the XCN and OCS ice features, respectively. The black dotted line shows the CO gas profile at each relevant temperature. The fitted laboratory profiles are described in the bottom left of each panel. The combined ice profile is described as the red solid line.

temperature of 200 K along with the deep Gaussian component of the XCN ice. After subtraction of those components, we fitted the CO ice absorption features of the protostars with the experimental profiles of CO-rich (CO:CO<sub>2</sub> = 100:70 at 10 K) and H<sub>2</sub>O-rich (H<sub>2</sub>O:CO = 100:20 at 10 K) ice mixtures. Only for the case of Perseus 3 does the H<sub>2</sub>O-rich ice mixture of H<sub>2</sub>O:CO = 100:10 at 10 K fit better than the H<sub>2</sub>O-rich ice mixture of H<sub>2</sub>O:CO = 100:20 at 10 K. We used a higher temperature condition for the CO ice (Gibb et al. 2004) to fit the absorption feature of AFGL 7009S. In the case of the background star, only the H<sub>2</sub>O-rich ice mixture was employed to fit its absorption feature. We have shown the best-fit results for the XCN ice and both the gas and ice absorption features of CO in Figure 6.

Consequently, we derived the column density of each ice component for our targets using those best-fit results. The column density errors for H<sub>2</sub>O, CO<sub>2</sub>, and OCS were estimated using the optical depth errors in their absorption area at 2.80

–3.20  $\mu\text{m}$ , 4.15–4.35  $\mu\text{m}$ , and 4.85–4.95  $\mu\text{m}$ , respectively. If the absorption area for the H<sub>2</sub>O ice was saturated, such as for AFGL 7009S, we adopted the error from the wavelength range between 2.8 and 2.9  $\mu\text{m}$ . We also calculated the column density error for the combined absorption of XCN and CO, dividing them into the 4.58–4.68  $\mu\text{m}$  and 4.60–4.75  $\mu\text{m}$  regions.

For the CO<sub>2</sub> ice, we compared the results of Perseus 1 and 2, RNO 91, and AFGL 7009S with those previously reported for Spitzer and ISO spectra (Gibb et al. 2004; Pontoppidan et al. 2008; Kim et al. 2012). The CO<sub>2</sub> ice column densities calculated from the stretching mode in this work are almost twice lower than those calculated from the bending mode except for Perseus 2. These differences could be attributed to an underestimated saturation effect because of the lower spectral resolution of IRC. The relative ice abundances of CO and CO<sub>2</sub> were calculated with respect to the H<sub>2</sub>O ice to avoid the effect of physical conditions such as source size. The derived column densities and their relative ratios for our targets

**Table 3**  
Ice Column Densities

Source Name	N(H <sub>2</sub> O) ×10 <sup>17</sup> (cm <sup>-2</sup> )	N(CO <sub>2</sub> ) ×10 <sup>17</sup> (cm <sup>-2</sup> )	N(CO) ×10 <sup>17</sup> (cm <sup>-2</sup> )	N(XCN) <sup>a</sup> ×10 <sup>17</sup> (cm <sup>-2</sup> )	N(OCS) <sup>b</sup> ×10 <sup>17</sup> (cm <sup>-2</sup> )
Perseus 1	68.12 ± 6.92	13.16 ± 3.60 28.62 ± 1.21 <sup>c</sup>	20.16 ± 2.09	0.28 ± 0.31	0.43 ± 0.06
Perseus 2	16.50 ± 1.11	5.66 ± 0.49 5.04 ± 0.13 <sup>c</sup>	3.74 ± 0.86	0.05 ± 0.18	0.12 ± 0.05
Perseus 3	43.25 ± 7.96	8.28 ± 0.99	6.50 ± 1.02	0.56 ± 0.22	0.24 ± 0.08
J03293654+3129465	10.65 ± 1.45	4.67 ± 0.89	12.76 ± 3.80	...	0.26 ± 0.05
RNO 91	22.80 ± 0.25 39.00 ± 5.00 <sup>c</sup>	7.29 ± 2.33 11.66 ± 0.16 <sup>c</sup>	6.78 ± 0.71 8.00 ± 0.30 <sup>c</sup>	0.33 ± 0.46	0.11 ± 0.04
AFGL 7009S	118.1 ± 17.30 110 <sup>d</sup>	11.02 ± 0.96 25 <sup>d</sup>	15.24 ± 0.72 18 <sup>d</sup>	1.21 ± 0.44 4.2 <sup>d</sup>	0.34 ± 0.04 0.11 <sup>d</sup>

**Notes.**<sup>a</sup> XCN column density is based on the assumption that XCN is OCN<sup>-</sup>. The band strength of OCN<sup>-</sup> is  $5 \times 10^{-17}$  cm molecule<sup>-1</sup> (Schutte & Greenberg 1997).<sup>b</sup> The band strength of OCS is  $1.5 \times 10^{-16}$  cm molecule<sup>-1</sup> (Palumbo et al. 1997).<sup>c</sup> Previous ground-based and Spitzer IRS results (Pontoppidan et al. 2008; Kim et al. 2012; Ioppolo et al. 2013) for our targets.<sup>d</sup> Previous ISO results (Gibb et al. 2004) for AFGL 7009S.

are summarized in Tables 3 and 4, respectively. In our analysis, due to the saturation effect, the H<sub>2</sub>O ice column density of RNO 91 was also underestimated compared to prior work (Pontoppidan et al. 2008). As a result, the derived CO<sub>2</sub> ice abundance relative to the H<sub>2</sub>O ice shows a similarity of  $\sim 0.3$  in both analyses (Table 4).

**5. Discussion***5.1. XCN Ice Feature*

Detection of the double-peaked absorption feature of pure CO<sub>2</sub> ice at 15.2  $\mu$ m has been considered strong evidence of episodic accretion because pure CO<sub>2</sub> ice can be produced by the evaporation of CO ice from a CO–CO<sub>2</sub> ice mixture or segregation from an H<sub>2</sub>O–CO<sub>2</sub> ice mixture on grain surfaces heated above the temperatures derived from the current luminosities (Lee 2007; Pontoppidan et al. 2008; Kim et al. 2012).

The XCN ice feature detected by AKARI IRC could be used as another piece of evidence of episodic accretion. In high-luminosity protostars such as AFGL 7009S, the strong XCN absorption feature has been considered as the result of the strong UV radiation from the central protostar. Therefore, the XCN absorption feature is not expected for low-luminosity sources. Consequently, the detection of the absorption features at 4.62  $\mu$ m (green solid lines in Figure 6) in our low-luminosity targets suggest that those low-luminosity sources had energetic burst events in the past. Kim et al. (2012) also detected the double-peaked feature of pure CO<sub>2</sub> ice in Perseus 1 and 2. RNO 91, which is believed to be undergoing an outburst event based on the broadened CO overtone absorption spectra in the *K* band (Yoon et al. 2021), shows the XCN ice feature as well as pure CO<sub>2</sub> ice features (Pontoppidan et al. 2008). Moreover, the detection of the crystalline components of H<sub>2</sub>O ice for all our low-luminosity targets also supports prior burst-accretion events because the crystallization of H<sub>2</sub>O ice reflects the thermal processing at high temperatures (Boogert et al. 2015).

*5.2. Ice Abundances*

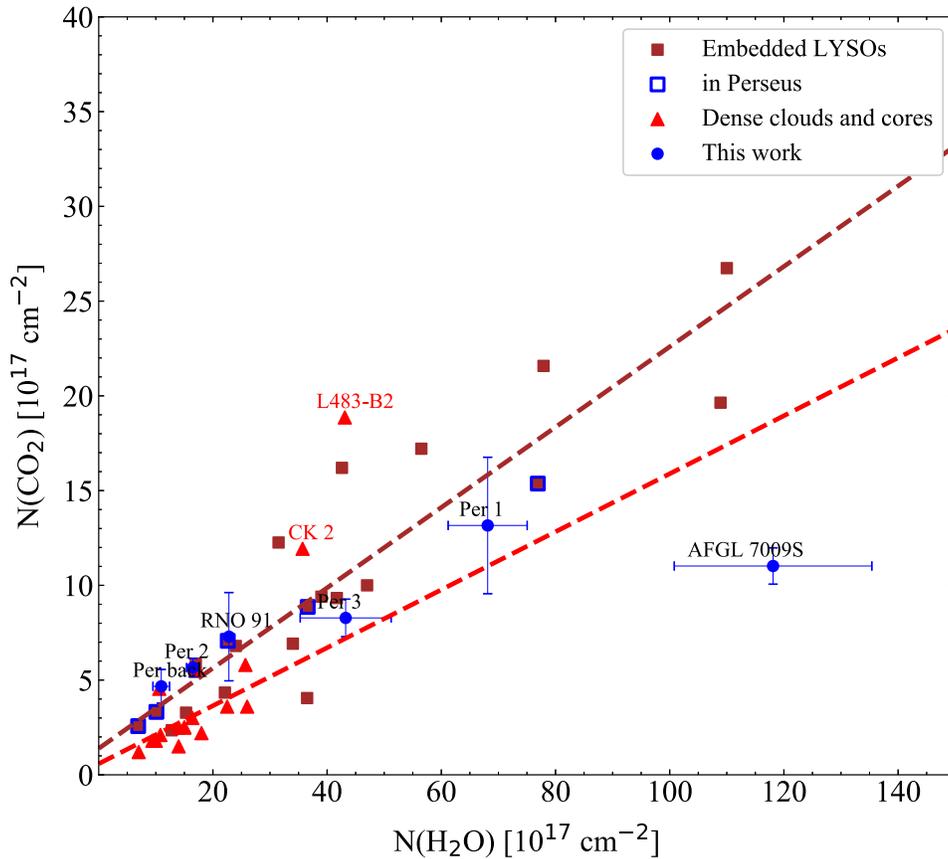
To understand the chemical evolution of ice in the circumstellar envelopes around low-luminosity protostars, we compared the ice abundances obtained from this study with

**Table 4**  
Ice Abundances

Source Name	Ice Abundances	
	X(CO <sub>2ice</sub> ) <sup>a</sup>	X(CO <sub>ice</sub> ) <sup>b</sup>
Perseus 1	0.19 ± 0.06 – 0.42 ± 0.05 <sup>c</sup>	0.30 ± 0.04
Perseus 2	0.31 ± 0.02 <sup>c</sup> – 0.34 ± 0.04	0.23 ± 0.05
Perseus 3	0.19 ± 0.04	0.15 ± 0.04
J03293654+3129465	0.43 ± 0.10	1.17 ± 0.38
RNO 91	0.30 ± 0.04 <sup>d</sup> – 0.32 ± 0.10	0.21 ± 0.03 <sup>d</sup> – 0.30 ± 0.03
AFGL 7009S	0.09 ± 0.02 – 0.23 <sup>e</sup>	0.13 ± 0.02 – 0.16 <sup>e</sup>
Embedded LYSOs	0.21 ± 0.02	0.15 ± 0.04
Dense clouds and cores	0.15 ± 0.05	0.30 ± 0.08

**Notes.**<sup>a</sup>  $X(\text{CO}_{2\text{ice}}) = \text{N}(\text{CO}_2)/\text{N}(\text{H}_2\text{O})$ .<sup>b</sup>  $X(\text{CO}_{\text{ice}}) = \text{N}(\text{CO})/\text{N}(\text{H}_2\text{O})$ .<sup>c</sup> Previous Spitzer IRS results (Kim et al. 2012) for Perseus 1 and Perseus 2. The H<sub>2</sub>O ice column densities from this work were adopted to calculate X(CO<sub>2ice</sub>).<sup>d</sup> Previous ground-based and Spitzer IRS results (Pontoppidan et al. 2008; Ioppolo et al. 2013) for RNO 91.<sup>e</sup> Previous ISO results (Gibb et al. 2004) for AFGL 7009S.

those of dense molecular clouds and cores as well as other embedded low-mass young stellar objects (LYSOs). In Figures 7 and 8, we have plotted the CO<sub>2</sub> and CO ice abundances with respect to H<sub>2</sub>O ice for our targets, LYSOs, and dense molecular clouds and cores together with their linear least squares fitting results. The ice abundances for the LYSOs were collected from the spectroscopic observational results obtained with the VLT, IRTF, Spitzer IRS, and AKARI IRC (Pontoppidan et al. 2003, 2008; Aikawa et al. 2012; Ioppolo et al. 2013). The selected LYSOs have evolutionary stages of 0–I (Ioppolo et al. 2013). The ice abundance data for the dense molecular cores were adopted from the AKARI program toward field stars behind quiescent cores ( $A_V > 6$  mag; Noble et al. 2013). The ice abundances of the dense molecular clouds ( $A_V > 10$  mag) were obtained from ground-based and Spitzer IRS data toward field stars behind the Serpens, Taurus, Lupus,



**Figure 7.** Relation between the column densities of H<sub>2</sub>O ice and CO<sub>2</sub> ice toward our targets (blue circles). Brown squares are the embedded LYSOs from Pontoppidan et al. (2008), Aikawa et al. (2012), and Ioppolo et al. (2013). The brown squares framed with blue denote the embedded LYSOs in the Perseus molecular clouds. The column densities of the dense molecular clouds and cores (red triangles) are from Whittet et al. (2007), Noble et al. (2013), and Chu et al. (2020). Each dashed line shows the best-fit results for the CO<sub>2</sub> ice abundances of the embedded LYSOs (0.21) and the molecular clouds and cores (0.15), respectively.

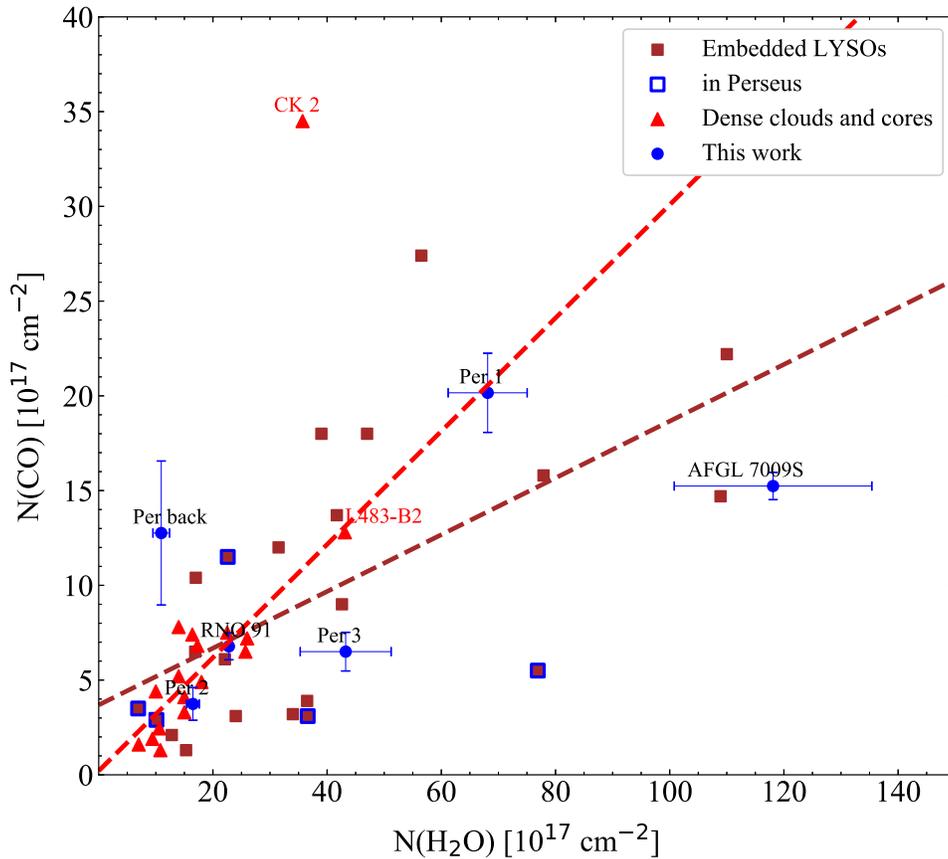
and LDN483 regions (Whittet et al. 2007; Boogert et al. 2011, 2013; Ioppolo et al. 2013; Chu et al. 2020).

Most of the LYSOs show higher values of CO<sub>2</sub> ice abundance than those of dense clouds and cores except for CK2 and L483-B2, which are denoted as red-colored text in Figure 7. This trend can be explained as follows: (1) most of the CO gas in the pre-stellar core is frozen onto the cold grain surfaces, which are coated predominantly by H<sub>2</sub>O ice. The reaction between CO and OH then leads to the formation of CO<sub>2</sub> ice in a H<sub>2</sub>O-rich ice mixture (Oba et al. 2010; Ioppolo et al. 2011). (2) The accretion rate of CO gradually increases with gas density, promoting CO<sub>2</sub> ice formation, and thus, increasing the amount of CO-rich CO<sub>2</sub> ice (Garrod & Pauly 2011; Öberg et al. 2011) in the dense envelope. (3) In the protostellar stage, grain surfaces heated by protostellar radiation evaporate CO molecules from the CO<sub>2</sub>-containing ices, leaving pure CO<sub>2</sub> ice (Öberg et al. 2009). Indeed, Pontoppidan et al. (2008) have detected the pure component of CO<sub>2</sub> ice from the double-peaked absorption feature at 15.2  $\mu$ m toward most of their observed LYSO targets. As a result, the CO<sub>2</sub> ice abundance increases as a protostar evolves.

For the background star behind the Perseus molecular cloud, the CO and CO<sub>2</sub> ice abundances do not follow the trend of other molecular clouds and cores. However, they have high values like measured for the Serpens and LDN483 regions, which are traced by spectra toward CK2 and L483-B2, respectively. For the case of CK2, its high-extinction line of sight ( $A_V \sim 40$  mag) and high CO<sub>2</sub> ice abundance may indicate

that the abundant gas-phase CO molecules lead to sufficient CO<sub>2</sub>-rich ice mixture formation, as well as CO ice (Whittet et al. 2007). Chu et al. (2020) suggested that the environment for ice chemistry toward the dense region ( $A_V \sim 40$  mag) presented by L483-B2 may not be affected by UV radiation or shocks from the nearby YSO. Therefore, high CO and CO<sub>2</sub> ice abundances for our background target may imply that the initial condition in the Perseus molecular cloud is comparable to those in the Serpens and LDN483 clouds.

For our low-luminosity targets, the CO<sub>2</sub> ice abundances follow a trend similar to that of the protostars in the Perseus region (brown squares framed with blue). This may indicate that their currently low luminosity is not an important parameter for CO<sub>2</sub> ice abundance. As seen in Figure 8, however, their CO ice abundances do not show a clear trend, unlike the CO<sub>2</sub> ice abundances. The CO ice abundance in Perseus 1 is more similar to those in the molecular clouds and cores, where most CO molecules are frozen on grain surfaces, rather than those of LYSOs, where the CO is gaseous within the CO sublimation radius. However, Perseus 2 and 3 show a relatively low abundance of CO ice, similar to that of AFGL 7009S, a massive protostar. This result may suggest that they had a strong or recent burst event. A strong burst can extend the CO sublimation region to a large radius and retard the refreeze-out of the sublimated CO due to the low densities at large radii. The deepest crystalline H<sub>2</sub>O and XCN ice features of Perseus 3 among the three low-luminosity targets support this interpretation.



**Figure 8.** The same plot as Figure 7, but for the CO ice. Each dashed line shows the best-fit results for the CO ice abundances of the embedded LYSOs (0.15) and the molecular clouds and cores (0.30), respectively.

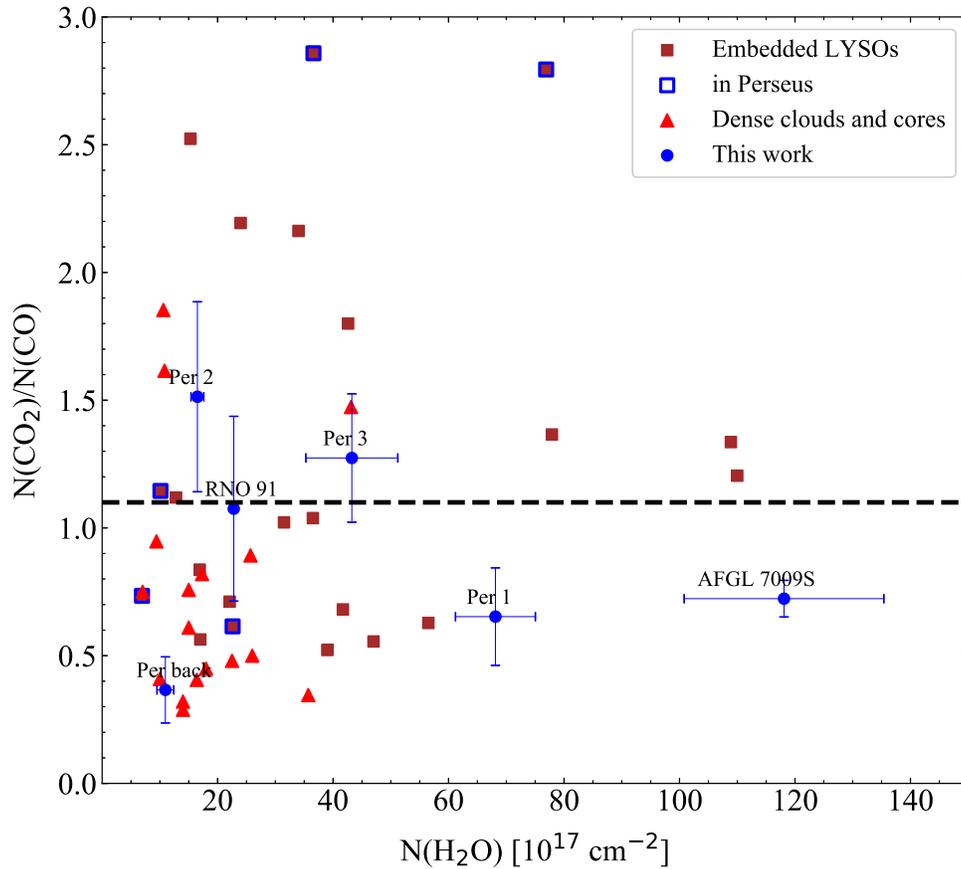
In the process of episodic accretion, the timescales of burst and quiescent phases are about 100 and 10,000 yr, respectively (Vorobyov et al. 2013). The sublimated  $\text{CO}_2$  during the burst events quickly returns to ice after the burst stops due to its higher binding energy (Vorobyov et al. 2013). On the other hand, the freeze-out timescale of CO is about 100,000 yr at a density of  $10^5 \text{ cm}^{-3}$  (Lee et al. 2004). Therefore, some of the CO sublimated during the previous burst events has not been fully frozen back onto the grain surfaces. In Figure 9, most of the protostars with the double-peaked feature of pure  $\text{CO}_2$  ice (Figure 4 in Pontoppidan et al. 2008) have an ice abundance ratio of  $\text{CO}_2$  to CO higher than 1.1. This might imply that protostellar heating by accretion episodes causes a decrease of the CO ice abundance (Öberg et al. 2011). Among our low-luminosity targets, Perseus 2 and 1 have the highest (1.5) and the lowest (0.7)  $\text{CO}_2/\text{CO}$  ice ratios, respectively. Considering the later evolutionary stage of Perseus 2 (Class I, Per-emb 38; Enoch et al. 2009) than Perseus 1 (Class 0, Per-emb 25; Enoch et al. 2009), Perseus 2 may have undergone more episodes of burst accretion, and a larger fraction of the sublimated CO ices may have remained in the gas phase.

A recent ALMA survey of  $\text{N}_2\text{H}^+$  (1–0) and  $\text{HCO}^+$  (3–2) toward protostars in the Perseus region have suggested timescales of the last burst event, using the emission peak radii of these two molecules (Hsieh et al. 2019). The  $\text{N}_2\text{H}^+$  and  $\text{HCO}^+$  peak radii reflect the CO and  $\text{H}_2\text{O}$  sublimation regions, where the gas-phase CO and  $\text{H}_2\text{O}$  destroy  $\text{N}_2\text{H}^+$  and  $\text{HCO}^+$ , respectively (Visser et al. 2015). Therefore, the estimated peak radius, which is larger than the expected value from the current luminosity, and the refreeze-out time of CO and  $\text{H}_2\text{O}$  provide

the peak luminosity of the past burst and the timescale after the burst. For Perseus 1 and 2, the  $\text{HCO}^+$  integrated intensity maps toward the central source enable measurements of the peak radius of the emission ( $0''.29$  and  $0''.05$ , respectively; Figure 9 in Hsieh et al. 2019). Assuming an  $\text{H}_2\text{O}$  refreeze-out time of 1000 yr (Visser et al. 2015), Hsieh et al. (2019) estimated that the timescales after the last burst for Perseus 1 and 2 are shorter than 1000 yr and longer than 1000 yr, respectively. However, for the case of Perseus 2, the detected  $\text{HCO}^+$  emission is too weak to estimate accurately its peak radius. Furthermore, its high  $\text{CO}_2/\text{CO}$  ice ratio and undetected  $\text{N}_2\text{H}^+$  emission may suggest that a large amount of the sublimated CO ices have not been frozen back onto the grain surfaces. Therefore, the last burst event for Perseus 2 should have occurred more recently than the case of Perseus 1.

## 6. Summary

We have carried out AKARI IRC spectroscopic observations of three low-luminosity protostars in the Perseus molecular cloud to trace their thermal histories, which are imprinted in their ice compositions on dust grain surfaces. We compared the ice abundances of these low-luminosity protostars with those of RNO 91, AFGL 7009S, and J03293654+3129465, which represent a low-mass protostar with a on-going burst accretion, a massive protostar, and a background star behind the Perseus molecular cloud, respectively. All our targets show absorption features of  $\text{H}_2\text{O}$ ,  $\text{CO}_2$ , and CO ices around 3.05, 4.27, and  $4.67 \mu\text{m}$ , respectively. We estimated the ice column densities by fitting those ice features with CDE-corrected laboratory



**Figure 9.** Ice abundance ratio of the  $\text{CO}_2$  to  $\text{CO}$  ices vs.  $\text{H}_2\text{O}$  ice column density. Dashed horizontal line denotes the minimum ratio for the embedded LYSOs that have the double-peaked absorption feature of pure  $\text{CO}_2$  ice (Figure 4 in Pontoppidan et al. 2008).

data, and we also identified thermally produced ice components, such as XCN, during past accretion bursts.

We compared the derived  $\text{CO}_2$  and  $\text{CO}$  ice abundances of the low-luminosity targets with those of embedded normal low-mass protostars and the dense molecular clouds and cores. Our results are summarized as follows:

1. The detection of the crystalline ice component of the  $\text{H}_2\text{O}$  absorption features toward the low-luminosity targets may support the idea that they have experienced higher luminosity phases that induced crystallization of amorphous  $\text{H}_2\text{O}$  ices. In the absorption band at  $4.62 \mu\text{m}$ , the XCN ice feature, which provides strong evidence of a past high-luminosity stage in currently low-luminosity protostars, was clearly detected for at least two targets (Perseus 1 and Perseus 3).

2. The  $\text{CO}_2$  ice abundances of our low-luminosity targets show a trend similar to those of the embedded low-mass protostars, indicating a common formation process of  $\text{CO}_2$  ice in the protostellar evolution and insensitive  $\text{CO}_2$  ice abundance to the accretion history.

3. The  $\text{CO}$  ice abundances of our low-luminosity targets show a scattered distribution, unlike the  $\text{CO}_2$  ice abundances. This result implies that different thermal conditions in the past accretion bursts and the timescale after the last burst have contributed to the refreeze-out of the sublimated  $\text{CO}$ .

4. Therefore, the  $\text{CO}_2/\text{CO}$  ice ratio can be used to estimate the timescale after the last accretion burst event as the combination of the  $\text{HCO}^+$  and  $\text{N}_2\text{H}^+$  emission peaks does.

5. For the case of Perseus 3, the past burst event is suspected to be much stronger than for the other low-luminosity targets, resulting in the deepest crystalline  $\text{H}_2\text{O}$  and XCN ice features.

6. The  $\text{CO}$  and  $\text{CO}_2$  ice abundances in the Perseus molecular cloud are relatively higher than those obtained from other dense molecular clouds and cores, probably because the abundant  $\text{CO}$  molecules promote those ice formation sufficiently in the Perseus molecular cloud.

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## References

- Aikawa, Y., Kamuro, D., Sakon, I., et al. 2012, *A&A*, 538, 57  
 Baba, S., Nakagawa, T., Shirahata, M., et al. 2016, *PASJ*, 68, 27  
 Bergin, E. A., Langer, W. D., & Goldsmith, P. F. 1995, *ApJ*, 441, 222  
 Bernstein, M. P., Sandford, S. A., & Allamandola, L. J. 2000, *ApJ*, 542, 894  
 Boogert, A. C. A., Blake, G. A., & Öberg, K. I. 2004, *ApJ*, 615, 344  
 Boogert, A. C. A., Blake, G. A., & Tielens, A. G. G. M. 2002, *ApJ*, 577, 271  
 Boogert, A. C. A., Chiar, J. E., Knez, C., et al. 2013, *ApJ*, 777, 73  
 Boogert, A. C. A., Gerakines, P. A., & Whittet, D. C. B. 2015, *ARA&A*, 53, 541  
 Boogert, A. C. A., Huard, T. L., Cook, A. M., et al. 2011, *ApJ*, 729, 92  
 Boogert, A. C. A., Pontoppidan, K. M., Knez, C., et al. 2008, *ApJ*, 678, 985  
 Boonman, A. M. S., & van Dishoeck, E. F. 2003, *A&A*, 403, 1003  
 Boonman, A. M. S., van Dishoeck, E. F., Lahuis, F., & Doty, S. D. 2003, *A&A*, 399, 1063  
 Brooke, T. Y., Sellgren, K., & Smith, R. G. 1996, *ApJ*, 459, 209  
 Chen, J.-H., Evans, N. J., II, Lee, J.-E., & Bourke, T. L. 2009, *ApJ*, 705, 1160  
 Chiar, J. E., Gerakines, P. A., Whittet, D. C. B., et al. 1998, *ApJ*, 498, 716  
 Chu, L. E. U., Hodapp, K., & Boogert, A. 2020, *ApJ*, 904, 86  
 Collings, M. P., Dever, J. W., Fraser, H. J., McCoustra, M. R. S., & Williams, D. A. 2003, *ApJ*, 583, 1058  
 Cutri, R. M., Skrutskie, M. F., van Dyk, S., et al. 2003, The IRSA 2MASS All Sky Point Source Catalog, NASA/IPAC Infrared Science Archive <https://irsa.ipac.caltech.edu/applications/Gator/>  
 d'Hendecourt, L., de Muizon, M. J., Dartois, E., et al. 1996, *A&A*, 315, L365  
 Dartois, E., Cox, P., Roelfsema, P. R., et al. 1998, *A&A*, 338, L21  
 Dartois, E., d'Hendecourt, L., Thi, W., Pontoppidan, K. M., & van Dishoeck, E. F. 2002, *A&A*, 394, 1057  
 Dartois, E., Gerin, M., & d'Hendecourt, L. 2000, *A&A*, 361, 1095  
 Dunham, M. M., Crapsi, A., Evans, N. J., II, et al. 2008, *ApJS*, 179, 249  
 Dunham, M. M., Evans, N. J., II, Terebey, S., Dullemond, C. P., & Young, C. H. 2010, *ApJ*, 710, 470  
 Ehrenfreund, P., Boogert, A. C. A., Gerakines, P. A., et al. 1996, *A&A*, 315, L341  
 Ehrenfreund, P., Boogert, A. C. A., Gerakines, P. A., et al. 1997, *A&A*, 328, 649  
 Enoch, M. L., Evans, N. J., II, Sargent, A. I., & Glenn, J. 2009, *ApJ*, 692, 973  
 Evans, N. J., II, Allen, L. E., Blake, G. A., et al. 2003, *PASP*, 115, 965  
 Evans, N. J., II, Dunham, M. M., Jørgensen, J. K., et al. 2009, *ApJS*, 181, 321  
 Evans, N. J., II, Lacy, J. H., & Carr, J. S. 1991, *ApJ*, 383, 674  
 Fraser, H. J., & van Dishoeck, E. F. 2004, *AdSpR*, 33, 14  
 Garrod, R. T., & Pauly, T. 2011, *ApJ*, 735, 15  
 Gerakines, P. A., Schutte, W. A., Greenberg, J. M., & van Dishoeck, E. F. 1995, *A&A*, 296, 810  
 Gibb, E. L., Whittet, D. C. B., Boogert, A. C. A., & Tielens, A. G. G. M. 2004, *ApJ*, 536, 347  
 Grim, R. J. A., Baas, F., Geballe, T. R., Greenberg, G. M., & Schutte, W. A. 1991, *A&A*, 243, 473  
 Grim, R. J. A., & Greenberg, J. M. 1987, *ApJL*, 321, L91  
 Hsieh, T.-H., Murillo, N. M., Belloche, A., et al. 2019, *ApJ*, 884, 149  
 Hudson, R. L., Moore, M. H., & Gerakines, P. A. 2001, *ApJ*, 550, 1140  
 Ioppolo, S., Sangiorgio, I., Baratta, G. A., & Palumbo, M. E. 2013, *A&A*, 554, A34  
 Ioppolo, S., van Boheemen, Y., Cuppen, H. M., van Dishoeck, E. F., & Linnartz, H. 2011, *MNRAS*, 413, 2281  
 Kim, H. J., Evans, N. J., II, Dunham, M. M., et al. 2011, *ApJ*, 729, 84  
 Kim, H. J., Evans, N. J., II, Dunham, M. M., Lee, J.-E., & Pontoppidan, K. M. 2012, *ApJ*, 758, 38  
 Lacy, J. H., Baas, F., Allamandola, L. J., et al. 1984, *ApJ*, 276, 533  
 Lacy, J. H., Carr, J. S., Evans, N. J., II, et al. 1991, *ApJ*, 376, 556  
 Lahuis, F., & van Dishoeck, E. F. 2000, *A&A*, 355, 699  
 Lee, J.-E. 2007, *JKAS*, 40, 83  
 Lee, J.-E., Bergin, E. A., & Evans, N. J., II 2004, *ApJ*, 617, 360  
 Lee, J.-E., Park, S., Green, J. D., et al. 2015a, *ApJ*, 807, 84  
 Lee, S., Lee, J.-E., & Bergin, E. A. 2015b, *ApJ*, 217, 30  
 Mayama, S., Tamura, M., Hayashi, M., et al. 2007, *PASJ*, 59, 1153  
 Mitchell, G. F., Maillard, J.-P., Allen, M., Beer, R., & Belcourt, K. 1990, *ApJ*, 363, 554  
 Noble, J. A., Fraser, H. J., Aikawa, Y., Pontoppidan, K. M., & Sakon, I. 2013, *ApJ*, 775, 85  
 Oba, Y., Watanabe, N., Kouchi, A., Hama, T., & Pirronello, V. 2010, *ApJL*, 712, L174  
 Öberg, K. I., Boogert, A. C. A., Pontoppidan, K. M., et al. 2011, *ApJ*, 740, 109  
 Öberg, K. I., Fayolle, E. C., Cuppen, H. M., van Dishoeck, E. F., & Linnartz, H. 2009, *A&A*, 505, 183  
 Ohyama, Y., Onaka, T., Matsuhara, H., et al. 2007, *PASJ*, 59, S411  
 Onaka, T., Kimura, T., Sakon, I., & Shimonishi, T. 2021, *ApJ*, 916, 75  
 Onaka, T., Matsuhara, H., Wada, T., et al. 2007, *PASJ*, 59, S401  
 Palumbo, M. E., Geballe, T. R., & Tielens, A. G. G. M. 1997, *ApJ*, 479, 839  
 Palumbo, M. E., Pendleton, Y. J., & Strazzulla, G. 2000, *ApJ*, 542, 890  
 Park, S., Lee, J.-E., Pyo, T.-S., et al. 2020, *ApJ*, 900, 36  
 Pendleton, Y. J., Tielens, A. G. G. M., Tokunaga, A. T., & Bernstein, M. P. 1999, *ApJ*, 513, 294  
 Pontoppidan, K. M., Boogert, A. C. A., Fraser, H. J., et al. 2008, *ApJ*, 678, 1005  
 Pontoppidan, K. M., Fraser, H. J., Dartois, E., et al. 2003, *A&A*, 408, 981  
 Schutte, W. A., & Greenberg, J. M. 1997, *A&A*, 317, L43  
 Shu, F. H., Adams, F. C., & Lizano, S. 1987, *ARA&A*, 25, 23  
 Skrutskie, M. F., Cutri, R. M., Stiening, M. D., et al. 2006, *AJ*, 131, 1163  
 Tegler, S. C., Weintraub, D. A., Rettig, T. W., et al. 1995, *ApJ*, 439, 279  
 van Broekhuizen, F. A., Keane, J. V., & Schutte, W. A. 2004, *A&A*, 415, 425  
 van Broekhuizen, F. A., Pontoppidan, K. M., Fraser, H. J., & van Dishoeck, E. F. 2005, *A&A*, 441, 249  
 van Dishoeck, E. F., Black, J. H., Boogert, A. C. A., et al. 1999, in *The Universe as Seen by ISO*, ed. P. Cox & M. F. Kessler (Paris: ESA Publications Division), 437  
 Visser, R., & Bergin, E. A. 2012, *ApJL*, 754, L18  
 Visser, R., Bergin, E. A., & Jørgensen, J. K. 2015, *A&A*, 577, A102  
 Vorobyov, E. I., & Basu, S. 2005, *ApJ*, 633, 137  
 Vorobyov, E. I., Baraffe, I., Harries, T., & Chabrier, G. 2013, *A&A*, 557, A35  
 Weingartner, J. C., & Draine, B. T. 2001, *ApJ*, 548, 296  
 Whittet, D. C. B., Pendleton, Y. J., Gibb, E. L., Boogert, A. C. A., Chiar, J. E., & Nummelin, A. 2001, *ApJ*, 550, 793  
 Whittet, D. C. B., Shenoy, S. S., Bergin, E. A., et al. 2007, *ApJ*, 655, 332  
 Whittet, D. C. B., & Tielens, A. G. G. M. 1997, in *ASP Conf. Ser. 122, From Stardust to Planetesimals*, ed. Y. J. Pendleton & A. G. G. M. Tielens (San Francisco, CA: ASP), 161  
 Yoon, S.-Y., Lee, J.-E., Lee, S., et al. 2021, *ApJ*, 919, 116  
 Zapata, L. A., Menten, K., Reid, M., & Beuther, H. 2009, *ApJ*, 691, 332