SPITZER SPACE TELESCOPE SPECTROSCOPY OF ICES TOWARD LOW-MASS EMBEDDED PROTOPLESTARS1, 2

A. C. Adwin Boogert, 3 Klaus M. Pontoppidan, 4 Fred Lahuis, 5, 6 Jes K. Jørgensen, 4 Jean-Charles Augereau, 4 Geoffrey A. Blake, 6 Timothy Y. Brooke, 3 Joanna Brown, 3 C. P. Dullemond, 7 Neal J. Evans, II, 8 Vincent Geers, 4 Michiel R. Hogerheide, 4 Jacqueline Kessler-Silacci, 4 Claudia Knez, 9 Pat Morris, 9 Alberto Noriega-Crespo, 9 Fredrik L. Schöier, 9 Ewine F. van Dishoeck, 4 Lorri E. Allen, 10 Paul M. Harvey, 8 David W. Koerner, 11 Lee G. Mundy, 12 Philip C. Myers, 10 Deborah L. Padgett, 10, 13 Annsela Sargent, 13 and Karl R. Stapelfeldt 13

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ABSTRACT

Sensitive 5–38 μm Spitzer Space Telescope and ground-based 3–5 μm spectra of the embedded low-mass protostars B5 IRS1 and HH 46 IRS show deep ice absorption bands superposed on steeply rising mid-infrared continua. The ices likely originate in the circumstellar envelopes. The CO2 bending mode at 15 μm is a particularly powerful tracer of the ice composition and processing history. Toward these protostars, this band shows little evidence for thermal processing at temperatures above 50 K. Signatures of lower temperature processing are present in the CO and OCN− bands, however. The observed CO2 profile indicates an intimate mixture with H2O, but not necessarily with CH3OH, in contrast to some high-mass protostars. This is consistent with the low CH3OH abundance derived from the ground-based L-band spectra. The CO2:H2O column density ratios are high in both B5 IRS1 and HH 46 IRS (~35%). Clearly, the Spitzer spectra are essential for studying ice evolution in low-mass protostellar environments and for eventually determining the relation between interstellar and solar system ices.

Subject headings: astrochemistry — infrared: ISM — ISM: abundances — ISM: molecules — stars: formation — stars: individual (B5 IRS 1)

1 INTRODUCTION

A recurring question in disk, planet, and comet formation studies is how the composition of molecular material evolves as it flows from the molecular cloud to the protostellar envelope and protoplanetary disk. Much of the material in these environments is frozen on grains. A plethora of processes, including heating by stellar photons, shocks related to accretion or outflow, cosmic-ray hits, and ultraviolet irradiation, can change the ice structure and composition. The spectroscopic effects of these processes can be observed in the vibrational bands of the ices through infrared spectroscopy. Ices around high-mass protostars have been extensively studied in this way. Infrared Space Observatory (ISO) spectra have shown that in particular the ice structure is affected by heating from the central star. The simplicity of the ice composition does indicate that the formation of new species through ultraviolet irradiation or cosmic-ray hits occurs at a low level at best. Observations of ices toward low-mass protostars have been limited because of the unavailability of much of the 5–20 μm spectral region, where many of the molecular bending-mode transitions occur. In particular, the CO2 bending mode at 15 μm is a valuable tracer of ice structure and composition (Ehrenfreund et al. 1998; Gerakines et al. 1999). With the sensitive Infrared Spectrometer (IRS; Houck et al. 2004) on board the Spitzer Space Telescope; Werner et al. 2004), this band can now be observed for the first time at high quality in low-mass systems.

Observations of two protostars are presented in this paper. B5 IRS 1 (IRAS 03445+3242; Beichman et al. 1984; L = 10 L⊙) is well studied at infrared and millimeter wavelengths (e.g., Charnley et al. 1990; Langer et al. 1996). The millimeter continuum emission is resolved on a few arcsecond scale, and it may originate in an inclined disk. The outflow has received most of the attention, and it has a large opening angle, leading to significant outflow/infall interaction. HH 46 IRS (IRAS 08242−5050; L = 12 L⊙) is also deeply embedded and is also the driving source of a powerful outflow. Spitzer imaging and spectroscopic observations of this source, focused on the outflow, are presented in Noriega-Crespo et al. 2004.

2 OBSERVATIONS

B5 IRS 1 and HH 46 IRS were observed with Spitzer IRS as part of the “c2d” Spitzer Legacy program (Evans et al. 2003) in the modules Short-Low (SL; λ s 5−14 μm; R = 64−128), Short-High (SH; λ = 10−20 μm; R = 600), and Long-High (LH; λ = 20−38 μm; R = 600). The archival Spitzer AOR keys

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2 The VLT ISAAC spectra were obtained at the European Southern Observatory, Paranal, Chile, in the observing program 272.C-5008.

3 Division of PMA, MC 105-24, California Institute of Technology, Pasadena, CA 91125.

4 SRON, P.O. Box 800, 9700 AV Groningen, Netherlands.

5 Division of GPS, MC 150-21, California Institute of Technology, Pasadena, CA 91125.

6 Max-Planck-Institut für Astrophysik, P.O. Box 1317, D-85741 Garching, Germany.

7 Division of Astronomy, University of Texas at Austin, 1 University Station C1400, Austin, TX 78712-0259.

8 Caltech/IPAC, MC 105-24, California Institute of Technology, Pasadena, CA 91125.

9 Smithsonian Astrophysical Observatory, 60 Garden Street, MS 42, Cambridge, MA 02138.

10 Department of Physics and Astronomy, Northern Arizona University, Box 6010, Flagstaff, AZ 86011-6010.

11 Department of Astronomy, University of Maryland, College Park, MD 20742.

12 Jet Propulsion Laboratory, California Institute of Technology, MC 183-900, 4800 Oak Grove Drive, Pasadena, CA 91109.

13 Jet Propulsion Laboratory, California Institute of Technology, MC 183-900, 4800 Oak Grove Drive, Pasadena, CA 91109.
are 0005638912 (HH 46 IRS) and 0005635328 (B5 IRS 1) for Program ID (PID) 172. Both sources are well centered in all slits. The integration time was 28 s per module per source at 14 s ramps, except for SH, which has 24 s in total and 6 s ramps. The spectra were reduced with the IRS pipeline version 9.5 on 2004 March 10 at the Spitzer Science Center. Bad pixels were interpolated in the spectral domain in the two-dimensional images before extracting one-dimensional spectra. Accurate wavelength calibration was assured using calibration tables available in 2004 May. For overlapping SH spectral orders, the poorly calibrated long-wavelength part of each order was removed. This is particularly important for obtaining a reliable profile of the CO 2 band at 15.2 μm, where two orders overlap. HH 46 IRS was observed independently as an Early Release Observation (PID 1063, AOR key 0007130112; Noriega-Crespo et al. 2004). The data sets are in good agreement and were averaged. Finally, complementary ground-based observations were obtained. B5 IRS 1 was observed with Keck NIRSPEC (McLean et al. 1998) at M-band and at Very Large Telescope ISAAC (Moorwood et al. 1999) L-band and M-band spectra of HH 46 IRS were obtained at R = 600 and 5000, respectively. The Spitzer and ground-based spectra were combined by scaling the ground-based data.

3. RESULTS

The combined Spitzer and ground-based 3–38 μm spectra of B5 IRS 1 and HH 46 IRS show steeply rising continua (Fig. 1). The continuum of HH 46 IRS is the steepest, with a 35/4 μm flux ratio of 100, compared to 10 for B5 IRS 1. Numerous silicate and ice absorption features are superposed. The main ice constituents are H2O, CO 2, and CO. The well-known, yet unidentified, 3.47 and 6.85 μm bands are present in both sources as well. Rarely seen before is a shallow absorption feature at 11.2 μm in both sources. It may be related to refractory dust components, such as crystalline forsterite (Kessler-Silacci et al. 2004). In addition, HH 46 IRS, but not B5 IRS 1, shows absorption by CH4 and “XCN” (likely OCN−; van Broekhuizen et al. 2004). Finally, other ice features may be present in the 5–10 μm region (NH3, HCOOH), but a dedicated analysis is required to verify their reality. We focus on the band profiles and abundances of the main ice components and their relation to the 15 μm CO 2 bands, discovered with Spitzer.

The CO2 bending mode has rarely been observed toward low-mass protostars, and never at such high quality. It is blends with the short-wavelength wing of the silicate bending mode. The CO2 band is put on an optical depth scale, assuming that the “intrinsic” profile of the silicate band is represented by the Galactic center source GC 3 (Chiar et al. 2000). For this a third-order polynomial is fitted to the wavelength regions 13.0–14.7 and 26.3–33.3 μm. The resulting CO2 bands look similar to those observed in other lines of sight (Fig. 2b); note in particular the presence of a long-wavelength wing extending to at least 16 μm (Gerakines et al. 1999). Similar to the massive protostar NGC 7538 IRS 9 weak double ice crystallization peaks are observed at the bottom of the band in HH 46 IRS, but not in B5 IRS 1. Neither B5 IRS 1 nor HH 46 IRS show evidence for a third peak at 15.38 μm, expected in CH2OH : CO2 complex formation.

To place the interpretation of the CO2 band within a larger perspective, ground-based observations of the 3.53 μm CH3OH band and the 4.67 μm band of solid CO are analyzed. The 3.53 μm band is superposed on the wing of the strong 3.07 μm H2O band and is locally blended with the unidentified 3.47 μm band. Following Brooke et al. (1999), we derive the continuum and separate the CH3OH contribution. For comparison, spectra of the massive protostars W33A (Brooke et al. 1999) and NGC 7538 IRS 9 (Boogert et al. 2004) are analyzed as well. Hints of CH3OH are seen in both HH 46 IRS and B5 IRS 1 (Fig. 2a), resulting in column densities of 7% with respect to H2O, comparable to NGC 7538 IRS 9, but much less than W33A. For HH 46 IRS the detection of CH3OH is strengthened by the presence of a feature at 9.7 μm in the bottom of the silicate band (Fig. 1). Both HH 46 IRS and B5 IRS 1 show prominent bands of solid CO at 4.67 μm (Fig. 2d). The ratio between the central narrow CO component and the broad long-wavelength wing, representing the column density ratio of volatile pure CO and CO mixed with less volatile H2O, is a factor of 5 smaller in HH 46 IRS. In fact, the profile of HH 46 IRS is comparable to that of the massive protostar W33A. The
latter two sources also show a band at 4.62 \( \mu \text{m} \), most likely attributed to the OCN\(^{-}\) ion. Relative to \( H_2O \), the OCN\(^{-}\) column density is comparable to (upper limits to) those of B5 IRS 1 and NGC 7538 IRS 9. The CO\(_2\) spectrum of B5 IRS 1 shows deep rovibrational gas-phase CO lines. The presence of gas-phase CO in HH 46 IRS is hard to assess because of telluric contamination. The intriguing differences and similarities between HH 46 IRS and B5 IRS 1, as well as compared to massive protostars, provide insight into the formation and evolution of interstellar and circumprotostellar ices.

Finally, column densities of the main ices, summarized in Table 1, are derived by dividing the integrated optical depth over the laboratory integrated band strength (e.g., Hudgins et al. 1993). Note that the CO\(_2\):H\(_2\)O ratios toward B5 IRS 1 and HH 46 IRS are significantly larger than the average over many, mostly massive protostellar sight lines (0.17 ± 0.03; Gerakines et al. 1999).

### 4. DISCUSSION

#### 4.1. Evolution of Ices in Low-Mass Environments

The formation and evolution of interstellar ices is, in principle, strongly dependent on local conditions such as the atomic hydrogen and carbon density, the temperature, the cosmic-ray flux, the ultraviolet photon flux, and the presence of shocks. Thus, key issues are the location of the ices along the absorption line of sight and the relative contributions from foreground clouds, envelopes, and inclined disks. The continuous rise of both the B5 IRS 1 and HH 46 IRS spectral energy distributions (SEDs) between 3 and 40 \( \mu \text{m} \), as well as the detection of extended submillimeter emission in James Clerk Maxwell Telescope archive images, are in favor of envelope-dominated models. We established the properties of these envelopes using the approach of Jørgensen et al. (2002). Adopting optical constants for bare and ice-coated silicate grains (Ossenkopf & Henning 1994), the 2–200 \( \mu \text{m} \) SED and the depth of the observed superposed ice and silicate bands were self-consistently modeled. The SED and silicate band depth of B5 IRS 1 are well fitted by the envelope models, and a significant fraction of the ices has evaporated. In contrast to B5 IRS 1, the submillimeter/far-infrared and mid-infrared Spitzer SED of HH 46 IRS cannot be simultaneously fitted. Possibly, this envelope is embedded in a larger scale, cold cloud not modeled within the framework of the simple spherical envelope.

Next we address the extent to which the ices in these envelopes have been processed. Several indicators are available. Laboratory experiments have shown that heating of ice...
mixtures with concentrations of $\text{CO}_2/\text{H}_2\text{O} \geq 1$ results in crystallization and an effective segregation of the $\text{CO}_2$ and $\text{H}_2\text{O}$ species. Spectroscopically, this is recognized as a double-peaked profile, characteristic of the pure $\text{CO}_2$ matrix (Ehrenfreund et al. 1998). Depending on the ice composition, the amorphous-to-crystalline phase transition occurs at 50–90 K in space, lower than the corresponding laboratory temperatures owing to the longer interstellar timescales (Boogert et al. 2000). Substructures are seen in the HH 46 IRS $\text{CO}_2$ band (Fig. 2b), but they are much weaker than some highly heated massive protostellar envelopes (Gerakines et al. 1999) and are absent in B5 IRS 1. In fact, the $\text{CO}_2$ band profile of HH 46 IRS is comparable to that observed toward one of the least processed envelopes, surrounding the massive protostar NGC 7538 IRS 9. In the simplest scenario of a single ice at one temperature, the mixture $\text{CH}_3\text{OH}:\text{H}_2\text{O}:\text{CO}_2 = 0.3:1:1$ (§ 4.2) must still have a laboratory temperature as high as 115 K, or $\sim 75$ K in space (Fig. 2b). In the more likely scenario of a temperature gradient along the line of sight, the bulk of the HH 46 IRS and B5 IRS 1 envelopes have temperatures well below 50 K. A fraction of the inner envelope of HH 46 IRS must be warmer, causing the observed weak substructures. Such two-component fits explain the observed profiles well (Fig. 2c).

More extensive processing at lower temperatures most likely has occurred within the envelopes, however. Unlike the massive protostar NGC 7538 IRS 9, the ground-based 4.67 $\mu$m spectra of solid CO toward HH 46 IRS and B5 IRS 1 show a weak central narrow component (Fig. 2d; Table 1). The most volatile CO-rich “apolar” ices may thus have evaporated (Tielens et al. 1991). HH 46 IRS shows a particularly broad profile, resembling the massive protostar W33A. Like W33A, HH 46 IRS shows an absorption feature at 4.62 $\mu$m, likely attributed to the OCN$^-$ species. This molecule may be produced from HNCO in the solid state at relatively low ice temperatures of less than 50 K (van Broekhuizen et al. 2004).

Concluding, while high-temperature ice processing, traced by the $\text{CO}_2$ band, is not observed in the low-mass envelopes, low-temperature (<50 K) processing may play a significant role. Qualitatively this is similar to some high-mass protostars (W33 A, NGC 7538 IRS 9). The proposed evolutionary sequence of ice processing in massive envelopes (Boogert et al. 2000; van der Tak et al. 2000) is indeed largely based on high-temperature indicators, such as ice crystallization, hot core gas temperatures, and gas/solid state ratios. These relations need to be investigated in a larger sample of low-mass protostars, in which the $\text{CO}_2$ band profile is a crucial tracer.

4.2. $\text{CH}_3\text{OH}:\text{CO}_2$ Complexes

The long-wavelength wing of the CO$_2$ bending mode may be a tracer of the presence of CH$_3$OH in the ices. CO$_2$ and CH$_3$OH form complexes, leading to an enhanced wing in some sources well fitted by laboratory ices with a CH$_3$OH:CO$_2$ mixing ratio of 1:1:1 (e.g., W33A in Fig. 2b). Recently, large abundances of CH$_3$OH of 25% with respect to H$_2$O were found in the envelopes of some low-mass protostars (Pontoppidan et al. 2003a). Clearly, B5 IRS 1 and HH 46 IRS both have lower CH$_3$OH abundances (Table 1). This is consistent with the weakness of the long-wavelength CO$_2$ wing. Indeed, laboratory mixtures with a CH$_3$OH:H$_2$O:CO$_2$ ratio of 0.3:1:1 fit the observed band well. The high CO$_2$ : CH$_3$OH column density ratio of $\sim 6$ toward these sources is, however, barely consistent with this laboratory mixture. Alternatively, the band profile can be explained by the combination of an abundant H$_2$O-rich ice responsible for the long-wavelength wing and an at least partly heated CO$_2$-rich ice responsible for the crystallization substructures seen in HH 46 IRS (Fig. 2c).

5. CONCLUSIONS AND FUTURE WORK

High-quality Spitzer observations of the CO$_2$ bending mode at 15 $\mu$m toward low-mass protostars offer a new tracer of ice mantle composition and evolution. The embedded low-mass systems B5 IRS 1 and HH 46 IRS show CH$_3$OH-poor ices with little evidence for 50–90 K thermal processing in their envelopes. Lower temperature processing appears evident in the solid CO band. These results form the basis for future studies on the physical and chemical state of ices entering protoplanetary disks and on how these and solar system ices are related. CO$_2$ bending-mode observations of more evolved systems and edge-on disks are required.

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