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An Ice Age JWST inventory of dense molecular cloud ices

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ABSTRACT

Icy grain mantles are the main reservoir of the volatile elements that link chemical processes in dark, interstellar clouds with the formation of planets and composition of their atmospheres. The initial ice composition is set in the cold, dense parts of molecular clouds, prior to the onset of star formation. With the exquisite sensitivity of JWST, this critical stage of ice evolution is now accessible for detailed study. Here we show the first results of the Early Release Science program "Ice Age" that reveal the rich composition of these dense cloud ices. Weak ices, including, ¹³CO₂, OCN⁻, ¹³CO, OCS, and COMs functional groups are now detected along two pre-stellar lines of sight. The ¹²CO₂ ice profile indicates modest growth of the icy grains. Column densities of the major and minor ice species indicate that ices contribute between 2 and 19% of the bulk budgets of the key C, O, N, and S elements. Our results suggest that the formation of simple and complex molecules could begin early in a water-ice rich environment.

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In molecular clouds, the volatile elements that make up life as we know it (carbon, hydrogen, oxygen, 48 nitrogen, and sulfur, i.e. CHONS) are locked up in ices on the surfaces of dust grains. Vibrational modes 49 of these molecular ices are observed in absorption against the near- and mid-infrared continuum provided 50 by field stars located behind clouds. Fully-resolved absorption bands have logarithmic depths directly 51 proportional to the ice column density along the line of sight, allowing model-independent assessment of 52 relative ice abundances within the same beam. At low extinctions in the outer regions of clouds, a mixture 53 of water (H₂O), methane (CH₄), and ammonia (NH₃) ice forms initially through accretion of atomic H in 54 combination with atomic $O^{1,2}$, $C^{3,4}$, and $N^{5,6}$ onto silicate/carbon-rich dust grains. Carbon dioxide (CO₂) 55 also forms efficiently in this water ice layer. In the densest and coldest cloud cores, carbon monoxide 56 (CO) freeze-out forms a CO-dominated ice phase^{7,8}, where CO_2 and other simple ice species continue 57 to form. CO and its reaction products can be hydrogenated to produce methanol $(CH_3OH)^9$ or have a 58 hydrogen atom abstracted¹⁰, and subsequent radical-radical reactions can also lead to the formation of 59 other complex organic molecules (COMs). These simple ices and methanol should provide the feedstock 60 for more complex COMs, such as the biomolecule glycine that is seen in comets¹¹, some of which are also 61 capable of forming under pre-stellar core conditions¹². Ground-based telescopes and space observatories, 62 like the Infrared Space Observatory (ISO)¹³, Spitzer¹⁴, and Akari¹⁵, have probed ice chemical evolution 63 along sightlines through the envelopes of nascent protostars. However, chemical assays of cloud ice have 64 been limited to regions with visual extinctions below $A_V \sim 50$ magnitudes, due to the faintness of field 65 stars seen at larger $A_V^{16, 17}$. 66

Here we report the first observations of pristine cloud ices at $A_V > 50$ towards two background 67 stars, NIR38 (11:06:25.57 -77:23:15.87, J2000) and SSTSL2J110621.63-772354.1 (hereafter "J110621", 68 11:06:21.64 -77:23:54.12, J2000), using the James Webb Space Telescope (JWST). These stars probe 69 dense lines of sight just outside the infalling envelope of a Class 0 protostar, Cha MMS1¹⁸ in the low-70 mass star forming region Chameleon I (192 pc,¹⁹). Initial calculations of their extinction based on the 71 intrinsic colors of K and G giant stars and mid-infrared photometry suggest values of $A_V \sim 60$ and 72 $A_V \sim 95$, respectively (see section 3.4 in²⁰), or N_H=1.1×10²³ cm⁻² and 1.7×10²³ cm⁻², respectively. 73 The observations presented here were obtained with NIRSpec²¹ Fixed Slit (FS) mode ($R \sim 2600, 2.7-5.3$ 74 μ m), NIRCam²² Wide Field Slitless Spectrograph (WFSS) mode (R~1600, 2.4–5.0 μ m), and MIRI²³ 75 Low Resolution Spectrograph (LRS) FS mode ($R \sim 100$, 5–14 μ m) (see Methods section for more details), 76 in order to cover all five major simple ice species, H₂O, CO₂, CO, CH₄, and NH₃, and the simplest COM, 77 CH₃OH. 78

The full, multi-instrument 2.5–13 μ m spectra towards both high-A_V background stars are presented in the top panel of Figure 1, with major solid-state features labeled. The identifications of features that we detect, tentatively detect, and do not detect are presented in Table 1. The spectra obtained from each

instrument are compared in Figure 2; NIR38 is detected in the continuum at 3.97 μ m by NIRSpec FS 82 with 547.1 \pm 2.6 μ Jy (S/N \sim 207) and NIRCam WFSS with 551.2 μ Jy, while its flux at 7.5 μ m with MIRI 83 LRS is 310.7 \pm 0.6 μ Jy (S/N \sim 499). J110621 was detected at 3.97 μ m by NIRSpec FS with 54.4 \pm 0.4 μ Jy 84 $(S/N \sim 145)$ and by MIRI LRS at 7.5 μ m with a flux of 39.7 \pm 0.2 μ Jy $(S/N \sim 208)$. This high sensitivity 85 allows us to detect both the expected strong absorption features of abundant ice species, as well as a 86 number of weak absorption features that are now detectable through quiescent molecular cloud lines of 87 sight (Figure 1, bottom, and Figure 3). For these spectra we fit a global continuum to specific continuum 88 regions (see Methods and Figure 1 caption) to calculate optical depths for these ices. 89 We report column densities and abundances relative to water of the different ice species in Figure 4 90

and Table 2, as determined from both global and local fitting of laboratory data (Table 3) to the optical
 depths over the whole wavelength range (see Methods and fits given by Extended Data Figures 1-3) and to
 individual ice features (see Supplementary Data Figures). We also consider the shape of the ice bands,

⁹³ Individual ice features (see Supplementary Data Figures). We also consider the shape of the ice band
 ⁹⁴ which depends on the local environment, in particular whether the ice is mixed with water or not.

95 Results

Ice inventory and new features - Both spectra in Figure 1 display all of the deep features that we expect to be associated with the main icy grain constituents: H₂O ice, the main isotopolog of both major C-bearing ices, ${}^{12}CO_2$ and ${}^{12}CO$, and rocky silicates. The column density of water ice increases from $N_{H2O} \sim 7 \times 10^{18} cm^{-2}$ to $N_{H2O} \sim 13 \times 10^{18} cm^{-2}$, respectively, between NIR38 and J110621, while CO₂ and CO are present at 10-20% and 20-40% of H₂O ice. Additionally, the sensitivity and spectral resolution of NIRSpec also allow us to detect a number of new features that probe the structure of these main ices, as well as the chemical diversity of additional small molecules in the ice.

Inorganic O- and C-ices - In these simple ice species, we see structure in the ¹²CO₂ stretching feature 103 at 4.27 μ m, with both an excess emission over the continuum in the blue wing at 4.2 μ m and a strong 104 absorbing red wing that extends to at least 4.35 μ m. While the continuum shape may change slightly 105 with future photospheric model fits, there is no physically motivated fit that could locally change the 106 continuum enough to erase the warped profile. A similar asymmetric profile is theoretically expected to 107 result from ice mantle growth²⁴. An analogous scattering profile is tentatively seen in the CO band at 4.7 108 μ m, where there is red-shifted absorption below the continuum. However, the blue-shifted CO excess 109 requires confirmation, as it overlaps other absorption features. We also detect both the combination mode 110 of ${}^{12}\text{CO}_2$ at 2.7 μ m and perhaps the dangling O-H mode of H₂O at 2.74 μ m (see Extended Data Figure 1, 111 panel b inset), the latter of which would signify that some fraction of the water ice is porous or mixed with 112 other species. The ¹³C isotopologs of CO₂ and CO are both detected (see Extended Data Figures 4 and 113 5, respectively), superimposed over the 4.6–5.0 μ m CO ro-vibrational gas phase lines originating in the 114 stellar photospheres of these background stars. The ${}^{12}\text{CO}_2/{}^{13}\text{CO}_2$ ratio ranges from 69-87 towards these 115 two lines of sight, while the 12 CO/ 13 CO ratio ranges from 99-169. 116

N-rich ices - We detect the main N-carrying ice, NH₃, in isolation at 9.1 μ m after the removal of the 117 broad 10μ m silicate feature profile from the optical depth spectrum (see Extended Data Figure 6), along 118 with a blended ammonium (NH₄⁺) feature at 6.85 μ m, which have both been seen before towards dense 119 cores. However, with JWST we are now able to detect the cyanate anion (OCN⁻) at 4.62 μ m, where it 120 overlaps with the blue scattering wing of 12 CO (Extended Data Figure 7). Ammonium (NH⁺₄), a potential 121 counter ion, is also detected, securing the identification of OCN⁻. In contrast, we do not detect other small 122 nitriles, such as CN, HCN, and CH₃CN (see Methods). The upper limits to these ice column densities 123 range from 0.7 to 2% of H_2O in our spectra. This limit is similar to the 0.1-1% level of HCN seen in 124 comets²⁵. 125



Figure 1. NIRSpec FS [NIRCam WFSS] and MIRI LRS spectra of NIR38 and J110621. Top: Full NIRSpec FS and MIRI LRS spectra of NIR38 ($A_V \sim 60$, solid navy line) and J110621 ($A_V \sim 95$, solid light gray line), with associated continuum fits (dotted lines).

For NIR38, a preliminary NIRCam WFSS spectrum has been scaled to the NIRSpec spectrum at 3.8 μ m and spliced in to cover the NIRSpec FS gap from 3.85–3.9 μ m and extend the spectrum to 2.5 μ m. Ice absorption features are color-coded according to species and labelled in the NIR38 spectrum. Wavelength regions used for the continuum fit are indicated by light gray bars (NIRSpec) and dark gray filled circles (MIRI) at the bottom of the top panel. Bottom: Zoom in on the weaker ice features and structure revealed by JWST. The potential dangling O-H feature is indicated by "dO-H", and the combination modes of CO₂ and H₂O by "combi."

S-rich ices - In these spectra, we detect the S-bearing ice species carbonyl sulfide (OCS) around 4.9 126 μ m, superimposed on the stellar photospheric CO absorption features (Extended Data Figure 8). The 127 simultaneous detection of OCS and CO ice is consistent with a solid-state formation mechanism of CO + 128 $S \rightarrow OCS^{26}$, but constraining the intimate chemical environment of OCS would require careful removal of 129 the photospheric features. There are hints of another S-bearing ice, SO₂, at 7.6 μ m in the blue shoulder of 130 the CH₄ feature, with detection limits of 0.1-0.3% with respect to water. The source of sulfur for OCS and 131 potentially SO₂ could be from gas-phase depletion into the ice^{27} , as well as from minerals, such as troilite 132 $(FeS)^{28}$. However, the dominant S-bearing ice in comets, hydrogen sulfide $(H_2S)^{29}$, remains undetected 133 at an upper limit of 0.6% of H₂O, as the 3.92 μ m feature is not detected towards NIR38. This limit is 134 comparable to the 1% level of H_2S seen in comets²⁵. 135

Organic ices - We detect both bands of the simple organic ice CH₄ for the first time in background



Figure 2. Data quality comparison for NIR38 and J110621. (Top panel) Comparison of the NIRCam WFSS (blue), NIRSpec FS (black), and MIRI LRS FS (red) spectra of the $A_V = 60$ background star. Error bars (gray) are 3σ , and in some regions are smaller than the thickness of the lines. Spitzer IRAC photometry (gold points) from the IPAC SEIP catalog is given for reference, with error bars and bandpass indicated. (Bottom panel) Comparison of NIRSpec FS and MIRI LRS FS data for the $A_V = 95$ star. Colors are the same as in the top panel.

stars, at 3.32 and 7.6 μ m. Another low-contrast feature appears from 3.35–3.6 μ m in the red wing of the 137 water ice band. This feature has been detected before towards background stars, but we detect it here with 138 a S/N of 150 and 70 in the A_V =60 and 95 sources, respectively. At this sensitivity, the feature separates 139 into four distinct peaks that are reproducible between the NIR38 NIRCam and NIRSpec spectra, as well 140 as between NIR38 and J110621 (see Methods). These features are consistent with a blend between the 141 C-H stretch of CH₃OH and a broad component centered at $3.47\mu m$ (Extended Data Figure 9). Ammonia 142 hydrates (NH₃ \cdot H₂O) are considered to be the primary contender for this broad component³⁰, but the 143 sensitivity of our observations will enable a differential diagnosis in a future work. As seen in previous 144 dense cloud spectra, methanol ice is detected additionally in isolation at 9.7 μ m and blended with the 145 NH_{4}^{+} feature at 6.85 μ m. There is excellent agreement between the column densities derived from both 146 methanol features ((See Supplementary Figure 2)). Although the 6 and 6.85 μ m features appear smooth at 147 $R \sim 100$ in both sources, there are weak but robust absorption excesses at 6.94, 7.06, 7.24, and 7.43 μ m, 148 (see Figure 3), attributable to the functional group in COMs caused by the asymmetric deformation mode 149 of CH_3^{31} , which has been tentatively detected with Spitzer¹⁴ and JWST³². These two bands are seen in the 150 IR spectra of acetone (CH₃COCH₃)³³, ethanol (CH₃CH₂OH)³¹, and acetaldehyde (CH₃CHO)³¹. These 151 background stars will require the higher spectral resolution of MIRI MRS to confirm these identifications, 152 determine the COMs chemical environment, and the degree to which complex chemistry has begun along 153 the J110621 sightline. 154 155

Stable ice chemical environment from $A_V \sim 20$ to 95 - The absolute column densities of most ice species are slightly larger towards J110621, as expected from the increase to $A_V \sim 95$. However, the ice inventory is very similar towards both sightlines, suggesting that although the total amount of ice



Figure 3. Detections of complex organic molecule (COMs) functional groups. Panels (a) and (b): Local continuum over the optical depth spectra of NIR38 ($A_V = 60 \text{ mag}$) and J110621 ($A_V = 95 \text{ mag}$) in the range between 6.9 and 8.6 μ m. Panel (c): Local continuum subtracted spectra of NIR38 ($A_V = 60 \text{ mag}$) and J110621 ($A_V = 95 \text{ mag}$) compared to laboratory IR spectrum of COMs (CH₃CHO - green line³¹, CH₃CH₂OH - orange line³¹, and CH₃COCH₃:CO - blue line³³) in the solid phase. The magenta line shows the laboratory spectra degraded to a resolving power of 150. The vertical lines indicate the match of the experimental data with the observations. The vibrational modes of the experimental data are indicated.

increases, the ice composition is set at a lower A_V. In fact, the relative column densities of the simple ices 159 from $60 < A_V < 95$ are broadly consistent with the ice evolution sequence proposed on the basis of *Spitzer* 160 observations from $20 < A_V < 50^{16}$, as exemplified by the comparison with the background star Elias 16 161 $(A_V \sim 19)$ in Figure 4 well as laboratory data and chemical modeling of this dense cloud region²⁰. These 162 results could suggest that, although CO ice is the second most abundant species detected in our spectra, 163 the local cloud gas density may be less than the limit of $n_H \sim 10^5 cm^{-3}$ required for CO to catastrophically 164 freeze out via collisions^{7,8}. Supporting this, initial modeling of the ¹²CO ice profiles (Extended Data 165 Figures 1 and 2) suggests that they may be dominated by a pure component, with two additional weaker 166 components mixed with methanol or CO_2^{16} . In contrast, the local ¹³CO₂ ice profiles of both stars suggest 167 that CO₂ is dominated by an intimate mixture with H₂O, with a lesser contribution from a CO-rich mixture 168 (Methods and Extended Data Figure 4). Additionally, based on comparisons between laboratory data and 169 the profiles of the ¹²CO and 9.7 μ m methanol bands, methanol seems to reside in environments containing 170 both H₂O and CO (see Methods, Extended Data Figures 1 and 2). The amount of methanol appears to 171 be approximately the same in both sources, based on both the 3.53 μ m and 9.7 μ m features. In contrast, 172 there are constant or increasing column densities of the simple hydrides, NH₃ and CH₄. 173



Figure 4. Barplots showing the derived ice column density for different species towards NIR38 ($A_V \sim 60$ mag) and J110621 ($A_V \sim 95$ mag). (Top) Column densities of the ice species identified in this work, compared to the literature values of Elias 16 ($A_V \sim 19 \text{ mag}$)³⁴. The column densities of the major ice components are from the global ENIIGMA fit (best of n=112 models), and we use the values from the local fits for the minor ice components. Black arrows indicate upper limits and error bars are taken from the global ENIIGMA fit, and for the minor ice components, we use the values from the global ENIIGMA fit, and for the minor ice components, we use the values from the local fits. Black arrows indicate upper limits and error bars are taken from the 3 σ confidence intervals.

174 Discussion

The sum of the column densities for both CO isotopolog ices and their potential reaction products is 175 less than the expected total CO column density from A_V for each line of sight, suggesting that at most 176 46% and 33% of the available CO gas has frozen out into ices towards NIR38 and J110621, respectively. 177 Although NIR38 samples a smaller total column of dust, its line of sight appears to pass closer to the 178 Class 0 protostar (see Extended Data Figure 10). If this region contains locally denser or colder dust, it 179 could explain the larger fraction of total CO that is frozen out onto the grains. These results imply that the 180 rich variety of ices that we see likely formed early, prior to catastrophic CO freeze-out, rather than later 181 through purely CO hydrogenation pathways. 182

The other ice column density results are also consistent with efficient, early formation of CO₂, NH₃, 183 and CH₄ in water-rich ices through H-addition and abstraction^{3,6,35,36}, followed by a small amount of the 184 subsequent CO-based chemistry that we would expect to see at these high extinctions. While methanol was 185 traditionally thought to form efficiently via successive CO hydrogenation, with H₂CO as an intermediate⁹. 186 it can also form earlier and more slowly in the H₂O-rich ice phase^{37, 38}. Our fit to the feature at 9.7 μ m 187 suggests that both formation pathways may operate in these ices. This conclusion is supported by the 188 detection of functional groups of COMs at 7-7.5 μ m towards pre-stellar sources that lie outside of the 189 coldest cores in this region, suggesting their early formation in the water rich phase¹⁰. Models predict 190

only ethanol at N~6-15×10¹⁶ cm⁻²,²⁰ which is broadly consistent with the optical depths at 7.2 μ m in both spectra, but not the other potential COMs species that could produce the other absorption features seen at 6.94, 7.06, and 7.34 μ m. Our detections of COM functional groups in these pre-stellar ices hint at the non-energetic complexity achieved in ices already before the formation of a hot protostellar core.

Accounting for the amount of C, O, N, and S in the ices is critical to determine the bulk volatile budget 195 of the stellar and planetary systems that will form within this molecular cloud. Comparing the column 196 densities of the detected ices for both NIR38 and J110621 with the expected cosmic abundances for C, O, 197 N, and S, we see at most 19% of the total O- and C-, 13% of the total N-budget, and 1% of the S-budget 198 in this dense cloud (see Methods). These numbers are similar to what has been previously reported for 199 protostars¹⁶, but now we are able to trace the budgets of these elements back to their initial conditions in 200 dense clouds. Most of the remaining budgets will be made up of refractory species, including silicates and 201 amorphous carbons, or other ices like N_2 that do not show spectral features at these wavelengths. Some of 202 the budget may additionally be accounted for in COMs that we cannot yet identify conclusively with the 203 MIRI LRS spectral resolution. 204

The profile distortions of the deepest ice bands show that the increase in H_2O , CO_2 , and CO is 205 accompanied by an increase in the size of these icy grains. The enhanced, red-shifted absorption wing, 206 as seen in H_2O and CO_2 (e.g.³⁹), in addition to the blue-shifted emission wing described earlier for the 207 12 CO₂ and possibly 12 CO ice features²⁴, are associated with scattering effects resulting from icy grain 208 growth to sizes on the order of the wave vector at which they are detected, i.e. a few microns. Whereas 209 red wing extinction due to scattering is a rather robust effect produced by larger grains, the intensity of the 210 blue emission excess can be highly variable. Its strength is highly sensitive to specific local changes in the 211 optical constants of the grains' core and mantle materials. The profiles of our observed CO₂ ice features 212 imply growth to sizes of around 1 μ m, as predicted by some grain growth models (e.g.⁴⁰,⁴¹). Despite 213 this relatively modest increase in maximum grain size, the observed growth occurs at the expense of the 214 smaller grains, which are depleted. Our observed change in icy dust grain size distribution would not only 215 influence the visual extinction but also reduce the total grain surface available for reactions in such dense 216 regions. However, our tentative detection of the OH dangling mode of H₂O near 2.7 μ m could suggest 217 that the water in these large grains is porous or mixed with other ices. In that event, the pore surfaces may 218 also provide space for additional reactions. 219

Detailed modelling to quantify the maximum grain size, shape, and porosity of these ices will be 220 presented in a future work. Further analysis of the reaction pathways and relative ice abundances requires 221 both chemical modeling and future observations of molecular clouds at both low and high Avs to confirm 222 when the simple hydrides are formed in relation to CO freeze-out. Complementary molecular gas phase 223 observations will also confirm the extent to which CO has frozen out in this region. Such work will in part 224 continue through another component of the Ice Age ERS program, in which we have obtained hundreds of 225 ice spectra in the same Chameleon I region with the new multi-object capabilities of NIRCam WFSS. By 226 combining these datasets, the superlative sensitivity, spectral resolution, and wavelength coverage with 227 JWST now enable us to fully probe the initial conditions of all of the major ices in molecular cloud cores 228 just prior to their collapse to form protostars. These new capabilities open the door to understanding the 229 formation and inheritance of these key CHONS-species through the star- and planet-formation process 230 and, ultimately, address what role they will play in shaping the chemistry on emerging planets. 231 232

233 Methods

234 Observations and data reduction

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NIRSpec: NIRSpec Fixed Slit (FS)²¹ observations of the targets NIR38 ($A_V = 60$) and SSTSL2J110621.63-236 772354.1 ($A_V = 95$) were taken on July 6, 2022 and July 8, 2022, respectively, using the G395H grating, 237 combined with F290LP blocking filter. Target acquisition was achieved using the Wide Aperture Target 238 Acquisition (WATA) method and the SUB2048 subarray with the CLEAR filter and a readout pattern 239 of NRSRAPID6 with an exposure time of 14.5 seconds for both sources. Spectra of the two stars were 240 obtained using the ALLSLITS subarray at four dither positions, spaced along the S200A2 slit. Each 241 integration was composed of 57 groups and 265 groups using the NRSRAPID readout pattern, for total 242 on-source exposure times of 1274.7 seconds and 5845.7 seconds, respectively. 243

The JWST calibration pipeline was used for detector level 1 processing to calculate rate files 244 from the uncalibrated ramps using version 1.7.1, Calibration Reference Data System (CRDS) context 245 jwst_0948.pmap, and the PUB CRDS server. The two-dimensional rate spectra were distortion 246 corrected using a second-order trace function derived from a commissioning observation of the standard 247 star TYC 4433-1800-1, observed as part of program PID 1128. The two-dimensional spectral dithers were 248 pairwise differenced to efficiently remove the background, and a one-dimensional spectrum from each 249 dither was then optimally extracted⁴² using a cross-dispersion profile calculated by median-collapsing each 250 dither in the spectral direction. An uncalibrated spectrum was then derived using a median for the four 251 separate dithers to remove most cosmic rays. Note that the observation of SSTSL2J110621.63-772354.1 252 used very long integrations (>1000 s), and suffers from large numbers of cosmic ray hits, not all of which 253 could be fully corrected. To flux calibrate the spectra, we extracted spectra from the identically-processed 254 level 1 rate files of the standard star observation of TYC 4433-1800-1 using the same grating and slit. By 255 dividing with the standard star spectrum, and multiplying by a model spectrum of the standard star, scaled 256 to $K_S = 11.584$ mag, we arrive at the final, calibrated spectra. This yielded excellent results, although the 257 direct use of the standard star leave a small number of artifacts from uncorrected hydrogen absorption lines 258 in the standard star spectrum. Note that this process does not rely on pipeline flat fields or calibrations, 259 which are not yet available. However, the wavelength calibration does use the solution from the pipeline. 260 Errors were formally propagated from pixel errors estimated by the ramps-to-slopes fits from the level 1 261 processing. 262

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NIRCam: NIRCam Wide-field Slitless Spectroscopic (WFSS)²² grism observations of the Cha-MMS 1 264 field were taken on July 3, 2022 with the F322W2 filter (2.5-4.0 μ m) using Grism C with NIR38 (A_V 265 = 60) residing in module A. We obtained 24 individual integrations of the field with a total exposure 266 time of 1.7 hours. We followed a data reduction routine similar to that in⁴³. We first reduced the grism 267 spectroscopic data with the standard JWST calibration pipeline v1.6.2 to the level of Stage-1, using the 268 default CRDS setup with JWST OPS and no modifications, i.e. CRDS context 0953, and then performed 269 2D sky-background subtraction using the sigma-clipped median images that were constructed from the 270 obtained WFSS data. Flat-field correction was also applied using the imaging flat data obtained with 271 the same filter. We then extracted the spectra of the two background stars using the optimal extraction 272 method⁴² from each individual integration, and co-added them together using the SpectRes package⁴⁴. 273 The wavelength and flux calibrations were performed using the in-flight measurements obtained with 274 JWST Commissioning Program #1076. At this stage, it is important to note that the current background 275 subtraction method has not been fully optimised, so small systematic offsets may exist within data. Addi-276 tionally, the optimal extraction method reduces, but may not entirely eliminate, potential flux contamination 277

from other nearby sources. Therefore we may be marginally overestimating the flux for our $A_V = 60$ source.

MIRI LRS: MIRI Low Resolution Spectrograph (LRS) Fixed Slit (FS)²³ observations of the targets 280 NIR38 ($A_V = 60$) and SSTSL2J110621.63-772354.1 ($A_V = 95$) were taken on July 4, 2022 and July 11, 281 2022, respectively. Target acquisition was achieved using the F560W filter with a FAST readout pattern 282 with 4 groups per integration for an exposure time of 11.1 seconds for both sources. These two targets 283 used observations with 40 groups per integration and 104 groups per integration, respectively, with 5 284 integrations per exposure with a two-nod dither pattern along the slit, for a total of 10 total integrations per 285 source and total exposure times of 1132.2 seconds and 2908.2 seconds, respectively. The FASTR1 readout 286 pattern was used. 287

We reduced the data with the same procedure for the two sources. We used the STScI JWST 288 pipeline (https://jwst-pipeline.readthedocs.io) version 1.8.2, the PUB CRDS server, and CRDS context 289 jwst_0986.pmap to obtain the Stage 1 and Stage 2 products. We started from the uncalibrated data 290 (Level1b, 'uncal' files). We ran the Detector1Pipeline with default parameters and the Spec2Pipeline step 291 by step. We used each dither position as a background image for the other and subtracted the background 292 pixel-wise. From the calibrated images ('cal' files), we extracted a one-dimensional spectrum from each 293 dither position using the optimal extraction method⁴² where a cross-dispersion profile is calculated by 294 median-collapsing the 2D spectral trace in the spectral direction. The spectra from both dither positions 295 were averaged to obtain a final spectrum. As a comparison, we extracted a spectrum using the JWST 296 Spec3Pipeline. We combined the two dither positions into a single image using the 'resample_spec' 297 step and extracted the 1D spectrum using the 'extract_1d' step. We defined the extraction region in 298 a custom reference file and disabled the offset that accounts for the expected location of the source 290 ('use_source_posn' set to 'False'). This ensured that the aperture was centered on the source. We also 300 extracted spectra from the 'cal' files using a simple aperture method (not relying on 'extract_1d') and 301 from the resampled image using the optimal extraction method. All these spectra are in good agreement 302 but the optimal extraction method applied on the 'cal' files provides a smoother spectrum, which we 303 kept for scientific interpretation. The CRDS context jwst_0986.pmap uses a wavelength calibration 304 that has been updated for MIRI LRS Fixed Slit after an initial mismatch that was found between the 305 flight calibration and the first extracted science spectra. This new wavelength calibration (encoded in the 306 'jwst_miri_specwcs_0005.fits' reference file) is in good match with the known spectral features detected 307 in our spectra. 308

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Data quality: The spectra from all three instruments are shown in Figure 2 for the $A_V=60$ star. The 310 flux calibration of these data is such that they match each other within their respective 3σ error bars. The 311 differences in the signal at the bottom of the 3 μ m H₂O feature are due to the increased sensitivity of 312 NIRSPEC FS relative to NIRCAM WFSS, but are within the error bars. Both stars are saturated in the 4.3 313 μ m ¹²CO₂ ice bands and we lose the signal at the bottom of these features, which occurs as well in the 3 314 μ m band of the A_V=95 star. The reproducibility of the spectral features between NIRCam and NIRSpec is 315 excellent, and the spectra are broadly consistent with the Spitzer IRAC photometry of this source given in 316 the SEIP Source List server (https://irsa.ipac.caltech.edu/cgi-bin/Gator/nph-dd), taking into account the 317 lack of convolution with the IRAC filter and the assumed color correction. 318

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Global continuum fit: The continuum shape of background stars, which is physically limited to be a stellar Rayleigh Jeans tail with ices superimposed on it, is fitted either with detailed stellar photosphere models or simple piece-wise polynomial continua to each star⁴⁶. We do not yet have photospheric models for these stars, so we use polynomial fits: in our case, one over the NIRSpec range and another over the

MIRI range. For NIR38 ($A_{\rm V}$ =60) we fit the continuum using a fifth order polynomial with continuum 324 points of 2.4-2.49 μm, 2.65-2.69 μm, 2.715-2.720 μm, 4.0-4.04 μm, 4.06-4.07 μm, 5.15-5.2 μm, 5.3-5.7 325 μ m. For J110621 (A_V=95), we fit the following continuum points: 2.74-2.78 μ m, 3.98-4.01 μ m, and 326 5.4-5.7 μ m. The continuum determination in the MIRI LRS range is not straightforward due to the 327 broad ice and silicate features. We determine the continuum on the MIRI LRS range (5.2–13 μ m) 328 using a second-order polynomial function. We set the continuum points at 5.2, 5.6, and 13.2 μ m for 329 NIR38 and J110621. Then we combine the two continua in a piece-wise fashion, with the cutoff between 330 them taken at 5.1 μ m. The continuum shape may change slightly when the more detail stellar model is 331 applied. However, our initial steps in stellar modeling (not discussed here) show good agreement with the 332 polynomial continuum fit found here. We estimate that the uncertainty introduced by the continuum is 333 within the uncertainty in the A-values used to derive the column densities. 334

The silicate absorption band is removed by a synthetic silicate spectrum composed of amorphous pyroxene⁴⁵ (Mg_{0.7}Fe_{0.3}SiO₃) and olivine⁴⁵ (MgFeSiO₄), as previously used in the literature⁴⁶ for background stars (see Extended Data Figure 6). We used the optool code⁴⁷ to create a synthetic spectrum assuming grains of 1 μ m. We aim at matching the spectral ranges between 8.3 and 8.7 μ m and between 10.1 and 10.4 μ m. In both sources, the absorption of pyroxene dominates over olivine at 9.8 μ m. For the $A_V = 60$ mag star, pyroxene and olivine corresponds to 60% and 40%, respectively, whereas for the the $A_V = 95$ mag star, the absorptions are 70% due to pyroxene and 30% due to olivine.

ENIIGMA global fitting and local fits: We used the ENIIGMA fitting tool^{?,49} to simultaneously fit 343 multiple features across the NIRSpec and MIRI/LRS range by scaling laboratory ice spectra to match 344 the optical depths in Figure 1. A full list with data used in this paper is shown in Table 3. It is worth 345 mentioning that these laboratory data are previously baseline corrected and noise smoothed at relevant 346 bands. No further processing is performed during the fitting procedure. In the fits, we assume saturated 347 bands at 3 μ m and 4.27 μ m because of negative fluxes. At these two bands, the fit is not limited by the 348 peak of the band. This is an important assumption to make to avoid underestimating column densities of 349 the molecules contributing to the absorption of these bands. ENIIGMA searched for the best combination 350 of experimental data measured at temperatures of 15 K or below. Motivated by previous works, we 351 explored combinations with ice mixtures composed of CO:CO₂⁵¹, CO:CH₃OH⁵², H₂O:CH₃OH⁵³ and 352 H₂O:NH₃³⁰, H₂O:CO₂:CH₄⁵⁶, and pure CO⁵⁵. In addition to these data, ENIIGMA tested other IR spectra 353 measured at temperatures below 16 K. We did not include the spectrum of the ammonium ion (NH_{1}^{+}) 354 in the global fits because it is not a consensus that the 6.85 μ m is attributed to this chemical species. A 355 dedicated study of this spectral feature will be performed in a follow-up paper by considering different 356 chemical environments where NH_4^+ . Additionally, since NH_4^+ is formed by a chemical reaction between 357 other molecules (e.g., NH₃, HNCO) induced by temperature (warm-up) or radiation (e.g., ultraviolet, 358 X-rays, cosmic rays), the spectrum shows other products that have to be taken into account when making 359 assignments of the IR bands. Overall, ENIIGMA provides a good global fit of the major ice components 360 in the observations, which are used to derive the ice column densities (see Table 2). They are calculated by 361 $N_X = \int \tau_V dv / A$, where $\int \tau_V dv$ is the integrated optical depth of a specific band, A is the band strength, 362 and X is the chemical species. The uncertainties are derived from 3σ confidence intervals based on 363 correlation plots shown in Extended Data Figure 3. Additional sources of uncertainties are not considered 364 in these values. ENIIGMA does not fit entirely the isotope bands of ${}^{13}CO_2$ and ${}^{13}CO$ at 4.38 μ m and 365 4.78 μ m, respectively. First, this is because the global fit limits the amount of the isotopes by the strong 366 12 CO₂ and 12 CO bands. Second, the isotope abundances in the gases used to make the ice samples in 367 the laboratory may not be the same as found in these astronomical targets. By performing local fits, the 368 chemistry of the isotope bands is better constrained (see Extended Data Figure 4). Nevertheless, the ice 369

column densities are similar to the values obtained with the global fits as seen in Table 2.

Local fits are also used to calculate the ice column densities of the major components (see Figure 371 1 of the Supplementary Data). For the H₂O ice, we scale the pure H₂O ice IR spectrum at 15 K^{54} to 372 match the ranges around 2.85–2.95 μ m and 3.17–3.23 μ m because of the saturation of the bands. The 373 broadband between 5 and 8 μ m are fitted by NH₄⁺ and H₂O as scaled to the 3 μ m band. Independently of 374 the global fit, the NH_4^+ spectrum can be locally scaled to the astronomical data since this method does not 375 take into account the contribution of the chemical specie at other wavelengths. The goal of the local fits is 376 to estimate the highest amount of a specific component to the absorption band including or not blending 377 effects with other molecules. Since the contribution of CH₃OH absorption is minimal at 6.85 μ m (see 378 Extended Data Figures 1 and 2), we do not include methanol in the local fit of this band. In the cases of 379 CO_2 , CO_2 , CO_3 , CH_4 , SO_2 , NH_3 and CH_3OH , we adopted Gaussian profiles to fit the $A_V=60$ mag and $A_V=95$ 380 mag spectra, and calculate the ice column densities. Around 4.67 μ m and 7.7 μ m, we adopted more than 381 one sub-component to fit the observations, following the previous studies of these two bands^{55,56}. For 382 CH₃OH, we also perform a local fit analysis around 3.5 μ m, and the column densities are similar to both 383 local and global fits at 9.8 μ m. The local column densities are compared with the global column densities 384 in the Supplementary Information to validate the global fits. 385 The ice column densities derived from the global and local fit are collated in Table 2. In Figure 4, 386

we show the column densities of the major ice species derived from the global fits and the minor species 387 derived from the local fits. Additionally, we show a comparison with the column densities derived for a 388 background star with $A_V = 19 \text{ mag}^{34}$. These column densities are normalized to H₂O ice in the bottom 389 panel of Figure 4. In the Supplementary Information, all the values from global and local fits, and from 390 the ranges reported in the literature are compared. A caveat in the ENIIGMA methodology, is that it does 391 not perform grain shape correction of the ice bands. Such a correction comes with a level of discussion 392 beyond the scope of this paper, for example, which grain shape better reproduces the observations, and 393 what are the size distributions. These geometry effects will be explored in a subsequent study. 394

395

Local continuum fit for weak features: To separate the weaker features from the wing of the water 396 stretch and combination bands, we also fit a local continuum to both spectra. The continuum points 397 were set to the following ranges: $3.215-3.231 \,\mu\text{m}$, $3.252-3.263 \,\mu\text{m}$, $3.289-3.295 \,\mu\text{m}$, $3.306-3.311 \,\mu\text{m}$, 398 $3.610-3.626 \ \mu\text{m}, 3.686-3.693 \ \mu\text{m}, 3.711-3.727 \ \mu\text{m}, \text{and } 3.759-3.795 \ \mu\text{m}.$ We calculated a fifth-order 390 polynomial to these regions and took the local optical depths with respect to this continuum. For ¹³CO, 400 CH₃OH, OCN⁻, and OCS we scaled laboratory data of simple ice mixtures to match the feature profiles. 401 The profile of the best fitting scaled laboratory mixture and band strengths were used to determine local 402 column densities, as described below. 403

404

3.4 - 3.6 μ m blended absorption (CH₃OH and NH₃ · H₂O): The absorption feature between ~3.35 - 3.6 405 μ m is likely caused by a combination of different ices and grain properties. However there is a distinct 406 peak at 3.53 μ m for both sources indicating the presence of CH₃OH ice (C-H stretching mode).¹⁶ In order 407 to constrain the CH₃OH ice abundance, we used the fifth order polynomial local baseline described above 408 to obtain the optical depths for this feature. Previous studies have fit a simple Gaussian to CH₃OH along 409 lines of sight toward background stars but this underestimates the red wing in the feature for both lines 410 of sight in this study.^{46,67} We therefore scaled laboratory spectra of pure CH₃OH ice at $15K^{31}$ to fit the 411 region and minimize the residuals between 3.53 and 3.65 μ m. We did not fit the laboratory data to shorter 412 wavelengths because the use of a local baseline instead of a global baseline cuts off some of the CH₃OH 413 ice profile. Additional absorbing species and scattering signatures may contribute to this absorption 414 feature. The column densities are calculated by integrating the scaled laboratory optical depths using a 415

band strength $A_{CH_3OH} = 1.6 \times 10^{-16}$ cm molec⁻¹ over the 2.778-3.704 μ m regime⁵⁸ and represent upper 416 limits to the amount of methanol present, due to the potential for additional absorption described above. 417 These results are presented in Table 2 as upper limits, and the fits for both sources are shown in Extended 418 Data Figure 9. 419 The peak near \sim 3.47 μ m has been previously attributed to the NH₃ · H₂O hydrates but this is still up 420 for debate.^{30,68} Nonetheless, we model the feature using a simple Gaussian at this time with a FWHM 421 of 0.1 μ m and a central peak at 3.47 μ m to understand how much this overlapping feature may reduce 422 the column density of the CH₃OH. We model the Gaussian and lab data simultaneously and minimize 423 the residuals of the sum of both fits between 3.4 - 3.65 μ m (Extended Data Figure 9). When doing 424 this we find that the column densities for CH₃OH are lower by $\sim 20 - 30\%$ (N= 4.1×10¹⁷ cm⁻² and 425 $N = 4.5 \times 10^{17}$ cm⁻² for the A_V = 60 and A_V = 95 sources, respectively). These column densities agree 426 with those found by using the ENIIGMA fits to the globally determined optical depths. Further follow-up 427 studies will model the full 3.4 - 3.6 μ m absorption feature and constrain the column densities not only for 428

429 CH₃OH, but also the other possible absorbing species.

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¹³CO₂: Extended Data Figure 4 shows the observed ¹³CO₂ feature, around 4.39 μ m, compared with 431 laboratory spectra of CO_2 in different ice mixtures, which peak at slightly different wavelengths depending 432 on the ice mixture. The peak of each laboratory spectrum is scaled to the observed ${}^{13}CO_2$ feature at the 433 wavelength corresponding to the peak of the laboratory data. Overall, the band of ${}^{13}CO_2$ in H₂O-rich 434 ice reproduces the peak and width of the observed feature. A weak blue shoulder around 4.384 μ m is 435 also noticeable and could possibly be due to a fraction of ¹³CO₂ mixed in CO. A detailed study of the 436 components that contribute to the 4.39 μ m feature, combined with an analysis of the CO₂ bands, can 437 provide more insights about the formation and chemical environment of solid CO₂ and its 13 C isotopologue, 438 and it will be the focus of a future work. In this work, we provide an estimate of the ¹³CO₂ column density 439 assuming that the 4.39 μ m band can be modeled using the laboratory spectrum of a CO₂:H₂O(1:10) ice at 440 10 K. The column density of 13 CO₂ is derived by scaling the laboratory spectrum to the optical depth of 441 the 4.39 μ m feature. A band strength of A = 7.8 × 10⁻¹⁷ cm molec⁻¹⁵⁷ is assumed for ¹³CO₂ asymmetric 442 stretching. The laboratory data used for the comparison are taken from^{69,70}. In these laboratory ices, 443 13 CO₂ is set at ratios of 12 CO₂/ 13 CO₂ ~ 90, which need not be the same ratio in the astronomical targets. 444 To calculate this ratio from the astronomical data, we divide the column densities derived with ENIIGMA 445 for the ${}^{12}\text{CO}_2$ feature by those derived here for the ${}^{13}\text{CO}_2$ feature, yielding a ratio of ${}^{12}\text{CO}_2/{}^{13}\text{CO}_2 \sim$ 446 69-87 ratio for these two targets. 447

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OCN⁻: In our analysis of the XCN band a single component fit is used and plotted in Extended Data Fig-449 ure 7. This is a Gaussian function with peak center at 2165.9 cm⁻¹ and FWHM=23 cm⁻¹ previously used 450 to reproduce laboratory spectra of OCN^{-71} and the XCN band of embedded young stellar objects.^{17,60,72,73} 451 Only data points on the blue wing of the XCN band are considered to avoid any contributions from the 452 CO-ice band to the fit. The Gaussian profile reproduces the red wing and the component of the XCN 453 band of both targets. In addition, the residuals are negligible, justifying the use of a single component. 454 OCN- ice column densities were estimated by integrating over the fitted Gaussian function and scaling 455 with a band strength A_{OCN^-} of 1.3×10^{-16} cm molec⁻¹⁷¹. The resulting column densities are listed in 456 Table 2, and they are in good agreement with values obtained for quiescent lines of sight in nearby clouds.⁶⁰ 457 458

⁴⁵⁹ ¹³**CO:** The region around 4.779 μ m shows a weak feature that can be associated with ¹³CO (Extended ⁴⁶⁰ Data Figure 5). This feature is contaminated by the presence of photospheric absorption lines, which ⁴⁶¹ makes the feature difficult to integrate cleanly. For this reason, the laboratory spectrum of pure CO ice at

- ⁴⁶² 15 K⁷⁴ was scaled to the astronomical data to derive the maximum abundance of this species in the spectra ⁴⁶³ of both background stars. The band strength value is $A = 1.3 \times 10^{-17}$ cm molec⁻¹.⁵⁷
- 464

OCS: The region around 4.90 μ m shows tentative detection that can be associated with the CO stretching vibration of the OCS molecule (Extended Data Figure 8). A comparison with laboratory infrared spectra of OCS-containing ices shows that this band in pure OCS ice is too broad compared to the feature seen toward the background stars. Previous studies showed that this absorption band is better modeled by CH₃OH:OCS-containing ices^{75, 76}. The column densities for OCS were derived using the profile of the OCS mixed in H₂O and a band strength value of A = 1.18 × 10⁻¹⁶ cm molec⁻¹⁶².

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Non-detections and upper-limits: With these high S/N data, we have placed strong constraints on 472 several ice species, including HDO, HCN, CH₃CN, H₂CO, and H₂S. H₂CO may still be present at low 473 levels in these spectra, but with the lower resolving power ($R \sim 100$) of MIRI LRS FS, it is not possible 474 to separate it from the blue wing of the H₂O bending mode at 6 μ m. In contrast, it was clearly detected 475 in a protostar with JWST's MIRI MRS mode $(R \sim 3000)^{32}$. HDO was tentatively detected with AKARI 476 at $\sim 4.1 \ \mu m$ with an abundance of 2-10% relative to H₂O towards several protostars and disks¹⁵. We 477 do not see an obvious feature there in these spectra, although reliable upper limits can only be obtained 478 after correction for the ${}^{12}CO_2$ blue scattering emission wing. Upper limits for the H₂S, CH₃CN, and 479 HCN abundances are estimated considering the noise level in the region where the strongest vibrational 480 feature of these molecules absorb. Here, the regions around 3.92 μ m, 4.44 μ m, and 4.76 μ m for H₂S, 481 CH₃CN, and HCN, respectively. The upper limits are calculated from the root mean squared (RMS) as 482 $N = RMS \times FWHM/A$, where FWHM and A are the full width at half maximum and band strength of 483 the absorption feature in the pure ice, respectively. The resulting 1σ upper limits in the abundances w.r.t. 484 H_2O ice is less than 1 % for H_2S in NIR38. Data covering this region is not yet available for J110621. For 485 HCN the upper limits w.r.t. H₂O ice is less than 1% for both sources. For CH₃CN the value is less than 486 2% for both sources. The FWHM and band strengths for the pure ices are taken from 62,65,66 . 487 488

The location of the background stars in their larger scale environments: Complementary information 489 about the larger scale environment is critical when interpreting the column densities inferred from the 490 ice observations. Extended Data Figure 10 shows a map of the H₂ column density maps extracted from 491 the larger scale Chamaeleon maps⁷⁷ created based on far-infrared data 70 to 500 μ m from the *Herschel* 492 Space Observatory's Gould Belt survey⁷⁸. The maps clearly show the decrease of the column density 493 from the peak near the Class 0 protostar ChamI-MMS with a more extended structure emcompassing also 101 the clump Cha1-C2¹⁸. The $A_V \approx 95$ star at a projected distance of 6600 au is located in the direction of 495 this core, while the $A_V \approx 60$ star at a projected distance of 5600 au is located in a direction orthogonal 496 to this structure from the Class 0 protostar²⁰. The H₂ column densities toward the two background stars 497 are similar within $\approx 10\%$, suggesting that the local conditions are similar, despite the difference in A_V . 498 The A_V we use was derived from average giant star colors²⁰; from these JWST spectra, a more detailed 499 fit taking into account the spectral type of these background stars will soon be possible, which may 500 reduce the difference in A_V . If the discrepancy remains, the difference in A_V could represent local radial 501 extensions of the cloud along the line of sight or a superposition of additional clouds along the line of sight. 502 Complementary observations, e.g. of gas-phase line tracers, are needed to assess whether there are dif-503 ferences in the densities, and thereby, e.g., the time-scales for freeze-out, toward the two differ significantly. 504 505

⁵⁰⁶ **Calculation of the icy C, O, N, and S budgets:** The column of molecular hydrogen is calculated for ⁵⁰⁷ each line of sight as $N_{H2} \sim 1.0 \times 10^{21} cm^{-2} A_V^{79}$. Assuming cosmic abundances for the combined volatile

and refractory abundances in the interstellar medium (ISM)⁸⁰, the molecular hydrogen column can be 508 converted into expected bulk budgets of C, O, N, and S. To determine what fraction of these budgets our 509 ices represent, we summed the column densities of all C-bearing, O-bearing, N-bearing, and S-bearing ice 510 species. For the O-bearing species, we doubled the column densities of ${}^{12}CO_2$, ${}^{13}CO_2$, and SO_2 to account 511 for the two oxygen atoms. For both NIR38 and J110621, we see only 19% of the total O-budget, 19% 512 and 14%, respectively, of the C-budget, and 13% of the N-budget and 1% of the S-budget for both. If we 513 assume the N_{H2}/N_{CO} conversion for molecular clouds⁷⁹, then the expected amount of total CO towards 514 NIR38 and J110621 are 1.08×10^{19} cm⁻² and 1.71×10^{19} cm⁻², respectively. 515

516 Data Availability

⁵¹⁷ Our raw data are available at the STScI MAST JWST archive, and our enhanced spectra are available as part ⁵¹⁸ of our ERS science enabling product deliverables at the following Zenodo DOI: 10.5281/zenodo.7501239

Code Availability

The ENIIGMA global fitting tool⁴⁹ is publicly available on GitHub at the following URL: https://github.com/willastro/E fitting-tool

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550 Author contributions

MKM originated the proposal, designed the observations, co-managed the team, determined the feature 551 optical depths and wrote much of the main text. WR performed global and local fitting to determine the 552 column densities, including the error analysis, and wrote part of the Methods section. KP contributed to 553 the observational design, reduced and optimized the NIRSpec data, wrote part of the Methods section, and 554 commented on the draft. NC reduced and optimized the MIRI LRS data to allow for the global fitting 555 and wrote part of the Methods section. LEUC performed the local fitting of the methanol + hydrates 556 band, wrote part of the Methods section, and commented on the draft. ED wrote part of the discussion 557 and made suggestions for the analysis. TL wrote portions of the results section and reorganized the draft. 558 JAN contributed to the original proposal, wrote portions of results section, and made suggestions for the 559 analysis. YJP managed the Overleaf file, wrote part of the results section, and made suggestions for the 560 local fitting. GP locally fit the OCN⁻ feature, wrote part of the Methods section, and commented on the 561 draft. DQ managed the Overleaf file and suggested parts of the results and discussion sections. MGR 562 did the local fitting of the ¹³CO₂, ¹³CO and OCS features, determined the upper limits, and wrote part of 563 the Methods section. ZLS and FS reduced the NIRCam data, with contributions to the reduction scripts 564 from HD, and wrote part of the Methods section. TB benchmarked the NIRSpec spectra to validate them. 565 ACAB helped to design the original program, co-managed the team, organized the NIRCam analysis, and 566 commented on the draft. WAB, PC, SBC, HC, MND, EE, JE, HF, RTG, DH, SI, IJS, MJ, JKJ, LEK, DCL. 567 MRSM, BAM, GJM, KIO, MEP, TS, JAS, EFvD, and HL commented on the draft. ZS, FS, EE, JE, HF, 568 and TS also contributed to the observational design and analysis of the NIRCam data. HL helped motivate 569 the original proposal, co-managed the team, and organized the laboratory data used for the analysis. All 570 authors participated in discussion of the observations, analysis and interpretation of the results. 571

572 Competing Interests

⁵⁷³ The authors declare no competing financial interests.

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λ (µm)	$v (cm^{-1})$	Species	Identification ^{<i>a</i>}	Detection	
		1		NIR 38	J110621
2.69	3708	CO ₂	combination	1	•••
2.73	3664	H ₂ O	O–H dangling bond	1	•••
3.0	3330	H ₂ O	O–H stretch	1	1
3.24	3249	CH ₃ OH	O–H stretch	1	1
3.32	3012	CH ₄	C–H stretch	1	1
3.47	2881	Ammonia hydrate	$NH_3 \cdot H_2O$!	!
3.32-3.64	3012-2890	CH ₃ OH	C–H asym. str. + overt.	1	1
3.92	2548	H_2S	S-H	X	•••
4.07	2457	HDO	O–D str.	X	×
4.17 - 4.77	2400 - 2100	H ₂ O	combination	1	1
4.27	2340	$^{12}CO_2$	C–O str.	1	1
4.38	2280	$^{13}CO_2$	C–O str.	1	1
4.44	2252	CH ₃ CN	C–N str.	X	X
4.59	2175	OCN^{-}	C–N str.	1	1
4.67	2140	¹² CO	C–O str.	1	1
4.76	2100	HCN	$C \equiv N$ str.	X	×
4.78	2090	¹³ CO	C–O str.	1	1
4.90	2040	OCS	C–O str.	1	1
6.0	1666	H ₂ O	bending	1	1
6.85	1459	CH ₃ OH	CH ₃ def.	1	1
6.85	1459	NH_4^+	N–H str.	1	1
6.9-7.5	1449-1333	Unidentified absorption	COMs functional groups?	1	1
7.24	1384	CH ₃ CH ₂ OH?	CH ₃ def.	!	!
7.43	1362	CH ₃ CHO?	CH ₃ def. + CH wag.	!	!
7.60	1318	SO_2	S–O str.	!	!
7.71	1300	CH ₄	C–H str.	1	1
8.86	1131	CH ₃ OH	CH ₃ rock	1	1
9.01	1110	NH ₃	umbrella	1	1
9.74	1025	CH ₃ OH	C–O str.	1	1
9.80	1020	Silicate	Si–O str.	1	1
11.0	910	H ₂ O	libration wing	1	1

Table 1. Absorption features of molecules in ices and dust features observed towards NIR38 ($A_V \sim 60$) and J110621 ($A_V \sim 95$).

^{*a*}Symbol legend: ✓- observed, X- not observed, ! - possibly observed, ... - insufficient data

Species	$v ({\rm cm}^{-1})$	$A \text{ (cm molec}^{-1})$	$\int au_{ m V}$	dv^{a}	$N_{\rm ice}$ [×10	$0^{18} \text{ cm}^{-2}]^{b}$
_			A _V =60	A _V =95	A _V =60	A _V =95
H ₂ O	3330	$2 \times 10^{-16} \text{ [ref.}^{57} \text{]}$	1376.07	2676.12	$6.88_{3.70}^{12.5}$ (6.93)	$13.38^{17.27}_{7.83}$ (13.17)
12 CO	2140	$1.1 \times 10^{-17} \text{ [ref.}^{57}\text{]}$	32.56	40.48	$2.96^{4.66}_{1.86}$ (3.22)	$3.68^{5.46}_{2.48}(3.94)$
¹³ CO	2090	$1.0 \times 10^{-17} \text{ [ref.}^{57}\text{]}$	0.32	0.31	$0.03^{0.04}_{0.02}$ (0.02)	$0.02^{0.03}_{0.01}$ (0.02)
$^{12}CO_2$	2340	$1.1 \times 10^{-16} \text{ [ref.}^{57}\text{]}$	151.8	191.4	$1.38^{1.97}_{0.77}$ (1.36)	$1.74_{1.09}^{2.36}$ (1.62)
¹³ CO ₂	2280	$7.1 \times 10^{-17} \text{ [ref.}^{57} \text{]}$	1.42	2.30	$0.02^{0.03}_{0.01}$ (0.03)	$0.02^{0.04}_{0.02}$ (0.03)
CH ₃ OH ^c	2830	$1.3 \times 10^{-16} \text{ [ref.}^{58}\text{]}$	53.3 {68.9}	58.5 {84.5}	0.41 {0.53}	0.45 {0.65}
CH ₃ OH	1025	$1.8 \times 10^{-17} \text{ [ref.}^{59}\text{]}$	10.98	9.18	$0.61^{0.95}_{0.28}$ (0.54)	$0.51^{1.08}_{0.24}$ (0.49)
NH ₃	1110	2.1×10^{-17} [ref. ⁵⁹]	6.31	13.86	$0.30^{0.97}_{0.21}$ (0.41)	$0.66^{1.11}_{0.48}$ (0.68)
CH ₄	1303	$8.4 \times 10^{-18} \text{ [ref.}^{59}\text{]}$	1.51	2.11	$0.18^{0.23}_{0.14}$ (0.16)	$0.25^{0.28}_{0.16}(0.28)$
OCN ⁻	2175	$1.3 \times 10^{-16} \text{ [ref.}^{60}\text{]}$	2.58^{d}	4.11 ^d	0.02	0.03
NH_4^+	1459	$4.4 \times 10^{-17} \text{ [ref.}^{61} \text{]}$	25.08^{d}	34.32^{d}	0.57	0.78
OCS	2040	$1.2 \times 10^{-16} \text{ [ref.}^{62}\text{]}$	1.18^{d}	2.36^{d}	0.01	0.02
SO ₂	1310	$3.4 \times 10^{-17} \text{ [ref.}^{64} \text{]}$	0.11^{d}	0.16 ^d	0.0034	0.0047
			1σ upper limits			
H_2S	2548	1.7×10^{-17} [ref. ⁶²]	0.64 ^e		0.04	
HCN	2100	1.0×10^{-17} [ref. ⁶⁵]	0.66 ^e	0.88 ^e	0.06	0.09
CH ₃ CN	2252	1.9×10^{-18} [ref. ⁶⁶]	0.26 ^e	0.35 ^e	0.14	0.19

Table 2. Integrated optical depths and column densities of molecules in ices observed towards AV60 and AV95 sources.

^aWhen not indicated, these values are based on the global fit.

^{*b*} Upper and lower values are from 3σ confidence intervals. Values inside the parenthesis are calculated from local fits. See Supplementary Information.

^c Calculations performed on optical depth data after local continuum extraction around 3.5 μ m. See Extended Data Figure 9. Values in the curly brackets are obtained excluding the ammonia hydrate effect.

^d Values from the local fits (see Supplementary Information).

 $e \int \tau_v dv = RMS \times FWHM.$

Label/Temp.	Temperature (K)	Database/Reference
H ₂ O	15 K	LIDA ⁵⁴
NH ₃	10 K	LIDA ⁸¹
CH ₄	10 K	LIDA ³³
СО	12 K	LIDA ⁷¹
CO_2	12 K	LIDA ⁷¹
CH ₃ OH	10 K	LIDA ³¹
NH ₃ :CH ₃ OH (1:1)	12 K	UNIVAP ⁴⁹
H ₂ O:NH ₃ (10:1.6)	10 K	
H ₂ O:CO ₂ (10:1)	10 K	LIDA ⁶⁹
H ₂ O:CO ₂ (1:10)	10 K	LIDA ⁶⁹
H ₂ O:CO ₂ (1:6)	10 K	LIDA ⁶⁹
$H_2O:CO_2$ (1:1)	10 K	LIDA ⁶⁹
H ₂ O:CO (20:1)	16 K	NASA/Ames ⁶³
H ₂ O:CH ₄ (20:1)	15 K	NASA/Ames ⁶³
H ₂ O:CO ₂ :CH ₄ (10:1:1)	12 K	UNIVAP ⁴⁸
H ₂ O:CH ₃ OH:CO ₂ :CH ₄ (0.6:0.7:1:0.1)	10 K	LIDA ⁷⁰
H ₂ O:CH ₃ OH:CO ₂ (9:1:2)	10 K	LIDA ⁷⁰
H ₂ O:CH ₃ OH:CO:NH ₃ (100:50:1:1)	10 K	NASA/Ames ⁵⁸
H ₂ O:CH ₃ OH (10:0.8)	10 K	
CO ₂ :CH ₃ OH (1:1)	10 K	LIDA ⁶⁹
CO:CO ₂ (1:1)	15 K	LIDA ⁷¹
CO:CH ₃ OH (4:1)	15 K	LIDA ⁵²

 $\label{eq:table_$

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1 Extended Data



Extended Data Figure 1. Global fit of the combined spectrum for NIR38. Combined NIRSpec and MIRI/LRS spectrum of the NIR38 source (black), with the ENIIGMA fitting tool model (green). Each component in the fit is colour-coded. Panel *a* shows the entire range between 2.5 and 13 μ m and the residuals of the fit. Panels *b-f* show a zoom-in of selected ranges corresponding to the major ice components. Small insets show the fit of ¹²CO₂ (Panel *b*), ¹³CO₂ (Panel *c*), ¹³CO (panel *d*) and CH₄ (panel *e*).



Extended Data Figure 2. Global fit of the combined spectrum for J110621. Combined NIRSpec and MIRI/LRS spectrum of the J110621 source (black), with the ENIIGMA fitting tool model (green). Each component in the fit is colour-coded. Panel *a* shows the entire range between 2.5 and 13 μ m and the residuals of the fit. Panels *b*-*f* show a zoom-in of selected ranges corresponding to the major ice components. Small insets show the fit of ¹³CO₂ (Panel *c*), ¹³CO (panel *d*) and CH₄ (panel *e*).



Extended Data Figure 3. Confidence interval analysis for the global fits to NIR38 and J110621. Corner plot showing the confidence interval analysis of the coefficients in the linear combination. The grey-scale contours show the differences in the χ^2 maps (Δ) which depends on the degree of freedom (ν) and the statistical significance (α). The yellow and red line contours indicate 2 and 3σ confidence intervals. The *left* and *right* plots are for $A_V = 60$ and $A_V = 95$ sources, respectively. Note that the ice species assigned to w1-w6 is automatically determined and differs between the left and right panels.



Extended Data Figure 4. Observed absorption profile of the ${}^{13}\text{CO}_2$ asymmetric stretching, around 4.39 μ m, in NIR38 (left panel) and J110621 (right panel). To demonstrate the ice chemical environment that best reproduces the observed feature peak, the colored curves show the scaled profiles of ${}^{13}\text{CO}_2$ in laboratory spectra of the following ice mixtures at 10 K: pure CO₂ (blue), H₂O:CO₂ (orange), CO₂:CO (green), and CO₂:CH₃OH (red). In all the ice mixtures, CO₂ is diluted in a ratio of ~1:10, with ${}^{12}\text{CO}_2/{}^{13}\text{CO}_2 \sim 90$.



Extended Data Figure 5. Observed absorption profile of the ¹³CO stretching, around 4.78 μ m, in the Av = 60 (left panel) and Av = 95 (right panel) sources. The laboratory spectra of pure ¹³CO ice at 10 K is also shown in blue.



Extended Data Figure 6. Silicate subtraction during optical depth calculation for NIR38 and J110621. MIRI/LRS spectrum of the two background stars before (black) and after (blue) silicate subtraction. The grey dashed line is the synthetic silicate spectrum used to remove the silicate absorption toward the background stars.



Extended Data Figure 7. Observed absorption profile of the OCN⁻ feature around 4.62 μ m, in the Av = 60 (left panel) and Av = 95 (right panel) sources. A gaussian fit using the parameters found in the literature² is also shown.



Extended Data Figure 8. Observed absorption profile of the C=O stretching of OCS, around 4.9 μ m, in the Av = 95 source. The colored curves show the profile of the OCS in laboratory ice spectra of pure OCS(blue), H₂O:OCS (orange), and CH₃OH:OCS (green), all at 17.5 K.



Extended Data Figure 9. Optical depths of the $A_V = 60$ (left) and $A_V = 95$ (right) background sources in the 3.2 - 3.8 μ m (3125 - 2631 cm⁻¹) region. Top: The red line shows the optical depths of CH₃OH laboratory data at 15K scaled for the C-H stretching band around the 3.53 μ m feature. Bottom: The blue Gaussian represents the likely NH₃ · H₂O component centered at 3.47 μ m and the red line again displays the CH₃OH laboratory data but both are simultaneously scaled so the sum (in green) fits the data from 3.40-3.65 μ m.



Extended Data Figure 10. Map of the column density distribution in the region inferred from the Herschel far-infrared maps from 70 to 500 μ m. The cyan plus-signs indicate the locations of the Class I protostar Ced 110-IRS4, the Class 0 protostar ChamI-MMS and the clump Cha1-C2 going from the north-east (top-left) to south-west (bottom-right). The yellow box and cross indicate the location of the $A_V \approx 60$ and the $A_V \approx 95$ background stars, respectively. The contours indicate increasing H₂ column densities in steps of 5×10^{21} cm⁻², starting at a value of 5×10^{21} cm⁻² for the lowest contour (yellow line).

1 Supplementary Information

To validate the column densities derived from the global fitting using multiple features and mixed ice
species, in Supplementary Figure 1 we show the local fits derived in the Main Text. In Supplementary
Figure 2 we compare those results with the column densities determined from the local fits. The column
densities from the local fits agree with those from the global fits to within the listed uncertainties.



Supplementary Figure 1. Local fits of the major ice components in NIR38 and J110621. At 3 μ m, we scale the H₂O ice spectrum at 15 K to match selected wavelengths that are not saturated (see Methods). Between 5.5 and 8.0 μ m, we sum the NH₄⁺ band and H₂O scaled to the 3 μ m profile. For the other absorption bands, we perform a Gaussian fit. In the cases of CO and SO₂/CH₄, more than one Gaussian profile is adopted.



Supplementary Figure 2. Barplot comparing individual column densities of ices derived from local fits to those derived from global fitting. (Top) Ice column densities towards NIR38 ($A_V = 60$ mag) and J110621 ($A_V = 95$ mag) derived from global (full bars, best of n=112 models) and local (hatched bars) fits. Blue and green lines indicate the range of values in the literature. Arrows are used for upper limits and error bars are from the 3σ confidence intervals. (Bottom) Relative column densities barplot of the detected ices, normalized to H₂O ice. Full and hatched bars are from global and local fits, respectively. Blue lines are from literature values, and arrows indicate upper limits. Error bars are from the 3σ confidence intervals.