Linking ice and gas in the Serpens low-mass star-forming region[★]

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ABSTRACT

Context. The interaction between dust, ice, and gas during the formation of stars produces complex organic molecules. While observations indicate that several species are formed on ice-covered dust grains and are released into the gas phase, the exact chemical interplay between solid and gas phases and their relative importance remain unclear.

Aims. Our goal is to study the interplay between dust, ice, and gas in regions of low-mass star formation through ice- and gas-mapping and by directly measuring gas-to-ice ratios. This provides constraints on the routes that lead to the chemical complexity that is observed in solid and gas phases.

Methods. We present observations of gas-phase methanol (CH₃OH) and carbon monoxide (¹³CO and C¹⁸O) at 1.3 mm towards ten low-mass young protostars in the Serpens SVS 4 cluster from the SubMillimeter Array (SMA) and the Atacama Pathfinder EXperiment (APEX) telescope. We used archival data from the Very Large Telescope (VLT) to derive abundances of ice H₂O, CO, and CH₃OH towards the same region. Finally, we constructed gas-ice maps of SVS 4 and directly measured CO and CH₃OH gas-to-ice ratios.

Results. The SVS 4 cluster is characterised by a global temperature of 15 ± 5 K. At this temperature, the chemical behaviours of CH₃OH and CO are anti-correlated: larger variations are observed for CH₃OH gas than for CH₃OH ice, whereas the opposite is seen for CO. The gas-to-ice ratios ($N_{\text{gas}}/N_{\text{ice}}$) range from 1–6 for CO and 1.4×10^{-4} – 3.7×10^{-3} for CH₃OH. The CO gas-maps trace an extended gaseous component that is not sensitive to the effect of freeze-out. Because of temperature variations and dust heating around 20 K, the frozen CO is efficiently desorbed. The CH₃OH gas-maps, in contrast, probe regions where methanol is predominantly formed and present in ices and is released into the gas phase through non-thermal desorption mechanisms.

Conclusions. Combining gas- and ice-mapping techniques, we measure gas-to-ice ratios of CO and CH₃OH in the SVS 4 cluster. The CH₃OH gas-to-ice ratio agrees with values that were previously reported for embedded Class 0/I low-mass protostars. We find that there is no straightforward correlation between CO and CH₃OH gas with their ice counterparts in the cluster. This is likely related to the complex morphology of SVS 4: the Class 0 protostar SMM 4 and its envelope lie in the vicinity, and the outflow associated with SMM 4 intersects the cluster. This study serves as a pathfinder for future observations with ALMA and the *James Webb* Space Telescope (JWST) that will provide high-sensitivity gas-ice maps of molecules more complex than methanol. Such comparative maps will be essential to constrain the chemical routes that regulate the chemical complexity in star-forming regions.

Key words. ISM: molecules – stars: protostars – astrochemistry – molecular processes – stars: low-mass – ISM: individual objects: Serpens

1. Introduction

The interplay between ice and gas in the Universe is an elusive relationship spanning from the formation of simple molecules to the creation of more complex organics; the building blocks of life in planetary systems like our own. In star-forming regions inside dense molecular clouds, the most likely mechanism to form complex organic molecules (COMs) is the thermal and energetic processing of ice-covered dust grains (Boogert et al. 2015; Öberg 2016). Unfortunately, detecting complex icy molecules is challenging because the vibrational modes of functional groups associated with these frozen molecules are blended in the infrared. So far, methanol (CH₃OH) is the most complex molecule that has been securely detected in the ices in the interstellar medium,

although ice features of a few other species, including acetaldehyde (CH₃CHO) and ethanol (CH₃CH₂OH), have also been suggested to contribute to the infrared spectra of young protostars (Schutte et al. 1999; Öberg et al. 2011a; Terwisscha van Scheltinga et al. 2018). Gas-phase (sub)millimetre single-dish and interferometric observations have demonstrated that a plethora of molecules more complex than methanol exist in the gas phase towards low- and high-mass star-forming regions (see e.g. reviews by Herbst & van Dishoeck 2009 and Jørgensen et al. 2020). One way to access the complex organic inventory of molecular ices consists of indirectly deriving ice abundances from gas-phase mapping (Whittet et al. 2011) and subsequently reverse-engineering their path into the gas phase to constrain their origins in the ices. However, this method relies on assumptions about how efficiently icy molecules are released into the gas. To investigate the ice-gas interaction in star-forming regions, combined gas and ice maps are required to constrain the physical

[★] The reduced datacubes are only available at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via <http://cdsarc.u-strasbg.fr/viz-bin/cat/J/A+A/643/A48>

and chemical environment. In this paper, gas and ice maps of methanol (CH_3OH) and carbon monoxide (CO) are presented. The data are used to determine CH_3OH and CO gas-to-ice ratios and thus to shed light onto the chemical processes occurring in cold low-mass star-forming regions.

Methanol is one of the key species in studies of the organic content of star-forming regions: it is the precursor of many complex organic molecules (Nuevo et al. 2018; Rivilla et al. 2019) and the ideal candidate to link gas and ice processes: at the low temperatures of cold environments, there is no efficient methanol formation path in the gas phase (Turner 1998; Garrod et al. 2007), but laboratory experiments have demonstrated that the production of methanol can successfully occur on ices at low temperatures (~ 10 K) through grain-surface hydrogenation reactions of CO ice (Watanabe & Kouchi 2002; Fuchs et al. 2009; Linnartz et al. 2015). After it has formed in the ices, the question remains at what level it is released back into the gas phase through thermal and non-thermal processes. Bertin et al. (2016) and Cruz-Diaz et al. (2016) have experimentally shown that the methanol desorption yield is at least one order of magnitude lower than the current value that is largely used in the literature and was measured by Öberg et al. (2009), which causes the methanol gas-phase abundance to be overestimated in astrochemical models. Theoretical three-phase chemical models that combine gas-phase chemistry with bulk and surface have addressed the effect of the reactive desorption (Dulieu et al. 2013) on the gas-phase abundance of molecules (Cazaux et al. 2016). In these models, neither photons nor cosmic rays play a role in the desorption mechanism, and the molecules are released into the gas phase upon formation on grains. Cazaux et al. (2016) showed that the gas-to-ice ratio for methanol is $\sim 10^{-4}$ at 10^5 years when the ice desorption is taken into account. In the opposite case, when the icy molecules are not released into the gas phase, the methanol gas-to-ice ratio is $\sim 10^{-6}$.

This prediction can be tested observationally by combining gas-phase and ice observations to directly measure the gas-to-ice ratios and desorption efficiency. Maps like this were created for carbon monoxide by Noble et al. (2017) for B35A, a star-forming dense core in Orion. The authors used data from the AKARI satellite and ground-based observations from the Institut de RadioAstronomie Millimétrique (IRAM) 30 m telescope and the *James Clerk Maxwell* Telescope (JCMT). Noble et al. (2017) concluded that there is no trivial relationship between ice and gas. No obvious trends were found between CO ice and gas-phase C^{18}O , suggesting that the interplay between CO freeze-out and desorption is complex in this region. Because methanol is the best candidate to bridge ice and gas chemistries, we have targeted the SVS 4 cluster, which currently holds the largest reservoir of ice methanol in the nearby star-forming regions (Pontoppidan et al. 2004).

SVS 4 is a small dense cluster located to the south-east of the Serpens molecular cloud. With 11 low- to intermediate-mass young stellar objects (YSOs) within a region of 20 000 AU, it is one of the densest YSO clusters ever observed (Eiroa & Casali 1989; Pontoppidan et al. 2003b; Eiroa et al. 2008). The SVS 4 young stars are all situated within $\sim 20''$ at most from one another, as shown in Fig. 1 and listed in Table 1. Additionally, the Class 0 protostar SMM 4, which has an outflow and a large envelope, is located only $26''$ (~ 10 000 AU) from the centre of the cluster. According to Pontoppidan et al. (2004), the cluster is located inside the south-eastern part of the envelope of SMM 4. As a result, lines of sight towards the SVS 4 stars probe the envelope material and the outflow of the Class 0 protostar. Among the SVS 4 cluster members, SVS 4–9 is an intermediate-mass YSO,

Fig. 1. Three-colour image of the SVS 4 cluster overlaid with SCUBA-2 850 μm density flux in mJy beam^{-1} (Herczeg et al. 2017). The contours are in decreasing steps of 10% starting at 3120 mJy beam^{-1} . The composite is made from *Spitzer* IRAC 3.6 μm (blue), 8.0 μm (green), and MIPS 24.0 μm (red) bands (Fazio et al. 2004). The dark orange crosses mark the position of the SVS 4 sources, and the white star represents SMM 4.

Table 1. Sample of sources.

Source	RA [J2000]	Dec [J2000]	A_J [mag]
SVS 4–2	18:29:56.58	+01:12:59.4	4.2
SVS 4–3	18:29:56.70	+01:12:39.0	18.0
SVS 4–4	18:29:57.00	+01:12:47.6	4.9
SVS 4–5	18:29:57.63	+01:13:00.2	21.0
SVS 4–6	18:29:57.69	+01:13:04.4	4.9
SVS 4–7	18:29:57.84	+01:12:27.8	10.5
SVS 4–8	18:29:57.88	+01:12:37.7	10.8
SVS 4–9	18:29:57.92	+01:12:46.0	10.5
SVS 4–10	18:29:57.88	+01:12:51.1	6.2
SVS 4–12	18:29:57.22	+01:12:58.4	26

Notes. The coordinates and the extinction in the J band (A_J) are from Pontoppidan et al. (2004). The estimated relative uncertainty on A_J is 5% (Pontoppidan et al. 2004).

and Preibisch (2003) found it to be the brightest X-ray source in the Serpens molecular cloud. SVS 4–3 and SVS 4–6 are also X-ray sources (Preibisch 2004; Giardino et al. 2007).

The ice content of the SVS 4 region has been investigated extensively by Pontoppidan et al. (2003a,b, 2004, 2008). These studies found that the SVS 4 cluster had one of the highest methanol ice abundances of low-mass stars (up to 28% relative to water ice and 3×10^{-5} compared to gas-phase H_2) reported to date (Pontoppidan et al. 2003a, 2004). The SVS 4 methanol ice abundance relative to water is comparable to the one observed towards the most methanol-rich massive stars known (Pontoppidan et al. 2003a). The nature of the Class 0 protostar SMM 4 itself has been extensively studied at millimetre and sub-millimetre wavelengths. These studies have revealed that the continuum emission towards SMM 4 is spatially

resolved into two Class 0 protostars, SMM 4A and SMM 4B, embedded in the same core (Lee et al. 2014; Aso et al. 2018; Maury et al. 2019). In contrast, little has been done to investigate the gas-phase molecular content of the outer envelope of SMM 4, where the SVS 4 stars are located. Öberg et al. (2009) observed methanol towards SVS 4–5 in the 2_K-1_K rotational band with the IRAM 30 m telescope providing a column density of $2.7 \times 10^{14} \text{ cm}^{-2}$ for a rotational temperature of about 8 K. Öberg et al. (2009) inferred that the spectrum of SVS 4–5 shows multiple emission components, which reflects the complexity of the cluster and also the contributions from the outflow associated with SMM 4. Kristensen et al. (2010) mapped the gas-phase methanol in the 7_K-6_K rotational band with JCMT towards SMM 4 and two outflow positions (SMM 4–W and SMM 4–S), and found a variation between 10^{14} and 10^{15} cm^{-2} that was attributed to the methanol sputtering triggered by the outflow. Other than methanol, Öberg et al. (2011b) observed a suite of molecular transitions for the complex organic O-bearing species HCOOCH_3 , CH_3CHO , and CH_3OCH_3 towards SMM 4 and SMM 4–W in $17''$ and $28''$ beams with IRAM, indicating a rich chemistry in the vicinity of SMM 4 and the low-mass outflow SMM 4–W.

In this paper we present millimetre interferometric and single-dish gas observations of methanol ($J=5_K-4_K$) and carbon monoxide (^{13}CO and C^{18}O , $J=2-1$) towards the Serpens SVS 4 cluster. In a complementary manner, we analyse L - and M -band infrared ice spectra of ten SVS 4 stars taken from the Very Large Telescope (VLT-ISAAC) archive¹. We combine gas- and ice-mapping techniques and directly measure CO and CH_3OH gas-to-ice ratios in the cluster. The resulting gas-ice maps and ratios serve to constrain the routes leading to chemical complexity in solid and gas phases of cold low-mass star-forming regions.

The paper is structured as follows. In Sect. 2 we present the ice and gas-phase observations together with the archival data. Section 3 summarises the method we adopted to derive the ice and gas column densities and reports the observational results. Section 4 interprets the gas-ice maps and analyses the gas and ice variations. Section 5 discusses the results and provides a comparison between observed and predicted CO and CH_3OH gas-to-ice ratios. Finally, Sect. 6 concludes the paper.

2. Observations and archival data

2.1. SMA and APEX observations

The SVS 4 cluster was observed on May 13, 2017, using the eight-antenna Submillimeter Array (SMA; Ho et al. 2004). The array was in its subcompact configuration, resulting in baselines between 8–45 m. The region was covered by two pointings whose dimensions are dictated by the SMA primary beam size of $50''$. The first pointing was centred on the Class 0 protostar Serpens SMM 4, and the second was offset by one half SMA primary beam to the south-east. The exact coordinates of the two SMA pointings are $\alpha_{J2000} = 18^{\text{h}}29^{\text{m}}57^{\text{s}}.63$, $\delta_{J2000} = +01^{\circ}13'00''.2$, and $\alpha_{J2000} = 18^{\text{h}}29^{\text{m}}57^{\text{s}}.88$, $\delta_{J2000} = +01^{\circ}12'37''.7$. The pointings covered frequencies ranging from 214.3 to 245.6 GHz with a spectral resolution of 0.6 MHz (0.78 km s^{-1}). Observations of the $\text{CH}_3\text{OH } J_K = 5_K-4_K$ branch at 241.791 GHz were made, and of $^{13}\text{CO } J=2-1$ at 220.398 GHz and of $\text{C}^{18}\text{O } J=2-1$ at 219.560 GHz were also made to compare methanol and CO emission (Table 2).

The data were calibrated and imaged using CASA² (McMullin et al. 2007). The complex gains were calibrated through observations of the quasars 1751+096 and 1830+063, and the bandpass and the flux calibrations through observations of the quasar 3c279 and Callisto, respectively. The resulting SMA dataset has a typical beam-size of $7''.9 \times 4''.0$ with a position angle of 68.8° .

Although the array was in this compact configuration, some emission is resolved out due to lack of short spacings. To map the extended emission towards the SVS 4 cluster, the SMA observations were therefore accompanied by short-spacing data obtained on May 10–14, 2017, with the Atacama Pathfinder EXperiment (APEX; Güsten et al. 2006). The observations covered frequencies between 218.2 and 220.7 GHz and between 241.3 and 243.8 GHz, corresponding to the SMA 230 GHz receiver lower and 240 GHz receiver upper sidebands.

The frequency resolution of the APEX observations is 0.076 MHz (0.099 km s^{-1}). The map size achieved with APEX is $75'' \times 100''$, and it fully covers the region mapped by the SMA primary beams. The coordinates of the APEX pointing are $\alpha_{J2000} = 18^{\text{h}}29^{\text{m}}57^{\text{s}}.76$, $\delta_{J2000} = +01^{\circ}12'49''.0$. A total integration time of 4.2 hours was adopted to match the sensitivity of the SMA data and to fold the datasets together. The APEX beam-size at the observed frequencies is $27''.4$. The reduction of the APEX dataset was performed with the GILDAS package CLASS³. Subsequently, the reduced APEX datacube was imported to CASA to perform the combination of interferometric and single-dish data.

The SMA and APEX data were combined following the procedure described in Appendix B.1. The species for which most of the flux is recovered in the combination is ^{13}CO , followed by C^{18}O and CH_3OH . The interferometric observations missed up to 90% of the emission, which implies that the gas column density would have been underestimated by approximately one order of magnitude. This illustrates how crucial the combination of interferometric and large-scale single-dish data is when the gas emission is extended and interferometric data have to be employed in a quantitative analysis (e.g. derivation of column densities).

2.2. VLT observations

Archival data from the VLT were used to constrain the CH_3OH and CO ice content of the SVS-4 region. L - and M -band spectra of ten SVS 4 sources (listed in Table 1) were obtained using the Infrared Spectrometer and Array Camera (ISAAC) mounted on the Unit Telescope UT1-Antu of the VLT. All the L -band data have previously been published in Pontoppidan et al. (2004) and were observed as part of programme 71.C-0252(A). Briefly, a low-resolution grating and $0''.6$ slit were used to cover the $2.80\text{--}4.15 \mu\text{m}$ spectral range, which yielded a resolving power of $\lambda/\Delta\lambda \sim 600$. In the case of SVS 4–5 and SVS 4–9, the brightest sources, the $3.53 \mu\text{m}$ feature related to the methanol C-H stretching was observed with a resolving power of 3300.

For the M -band observations, two sources (SVS 4–5 and SVS 4–9) were observed on May 6, 2002, as reported by Pontoppidan et al. (2003b), and M -band spectra of eight other sources were obtained between May 2005 and August 2006, and are presented for the first time in this paper. The M -band spectra used the medium-resolution grating and the $0''.3$ or $0''.6$ slit, depending on source brightness, to yield resolving powers of $\lambda/\Delta\lambda$ 5000–10 000 and a wavelength of $4.53\text{--}4.90 \mu\text{m}$. Standard

¹ <http://archive.eso.org/wdb/wdb/eso/isaac/form>

² <http://casa.nrao.edu/>

³ <http://www.iram.fr/IRAMFR/GILDAS>

Table 2. Spectral data of the detected molecular transitions.

Transition	Frequency ^(a) [GHz]	A_{ul} ^(a) [s ⁻¹]	g_u ^(a)	E_u ^(a) [K]	n_{cr} ^(b) [cm ⁻³]
C ¹⁸ O $J = 2-1$	219.560	6.01×10^{-7}	5	15.9	1.9×10^4
¹³ CO $J = 2-1$	220.398	6.04×10^{-7}	5	15.9	2.0×10^4
CH ₃ OH $J = 5_0-4_0$ E ⁺	241.700	6.04×10^{-5}	11	47.9	5.5×10^5
CH ₃ OH $J = 5_1-4_1$ E ⁻	241.767	5.81×10^{-5}	11	40.4	4.8×10^5
CH ₃ OH $J = 5_0-4_0$ A ⁺	241.791	6.05×10^{-5}	11	34.8	5.0×10^5
CH ₃ OH $J = 5_1-4_1$ E ⁺	241.879	5.96×10^{-5}	11	55.9	4.6×10^5
CH ₃ OH $J = 5_2-4_2$ E ⁻	241.904	5.09×10^{-5}	11	60.7	4.2×10^5

Notes. ^(a)From the Cologne Database for Molecular Spectroscopy (CDMS; Müller et al. 2001) and the Jet Propulsion Laboratory catalogue (Pickett et al. 1998). ^(b)Calculated using a collisional temperature of 10 K and collisional rates from the Leiden Atomic and Molecular Database (LAMDA; Schöier et al. 2005). The references for the collisional rates are Yang et al. (2010) for the CO isotopologues and Rabli & Flower (2010) for CH₃OH.

on-source integration times were ~45 min per pointing. The total integration time was doubled to 90 minutes for the faintest sources. The observations were carried out in pairs; each pointing was rotated to observe two stars at the same time. The data were reduced following the procedure described in Pontoppidan et al. (2003b). The spectra were flux calibrated with respect to the standard stars HR 6629 and HR 7236 and wavelength calibrated to remove telluric absorption lines.

3. Results

This section provides a summary of the methods we used to calculate the ice and gas-phase column densities presented in Sects. 3.1 and 3.2. Comprehensive descriptions of the methods applied when fitting the observational infrared data and producing the gas-phase maps are given in Appendices A and B.

3.1. Ice column densities

To investigate the spatial distribution of ices towards the SVS 4 cluster, accurate ice column densities must be derived. To accomplish this, the spectrum was divided by a continuum and the optical depth was derived using the formula $\tau_\lambda = -\ln(F_\lambda^{\text{obs}}/F_\lambda^{\text{cont}})$, where F_λ^{obs} is the observed flux and F_λ^{cont} is the continuum. A combination of blackbodies was used to determine the dust continuum for the *L* bands, whereas a spline function was adopted for the *M* bands. Table A.1 lists the photometric points used in the determination of the *L*-band continuum.

Following the τ calculation, the spectral decomposition of the observational data was carried out with the OMNIFIT⁴ fitting utility (Suutarinen 2015b): OMNIFIT is an open-source Python library used to fit observational data of astrophysical ices using multi-component laboratory spectra and analytical data. It makes use of the LMFIT package⁵ to perform the optimisation. In the *M*-band fitting, the non-linear optimisation by the Levenberg-Marquardt method was adopted, whereas the simplex Nelder-Mead and Monte Carlo Markov chain were used in the *L*-band fitting. The selected laboratory ice data were fitted to the observational spectra by applying a scale factor k . OMNIFIT provides a specific scale factor for each laboratory

Table 3. Fit parameters used to fit the infrared spectra with OMNIFIT.

<i>L</i> -band fitting			
Components	Fitting range ^(a)	Scale factor (k) ^(b)	Refs. ^(c)
pure H ₂ O	1–3	vary	5
H ₂ O:CH ₃ OH	1–3	vary	6
CO:CH ₃ OH	1–3	<i>M</i> -band values	7
<i>M</i> -band fitting			
Components	Fitting range ^(a)	Scale factor (k) ^(b)	Refs. ^(c)
CO:CH ₃ OH	4	vary	7
CDE-Lorentzian	4	–	8

Notes. ^(a)The fitting ranges are [1] 2.85–2.94 μm , [2] 3.17–3.23 μm , [3] 3.77–4.0 μm , and [4] 4.62–4.72 μm . The goodness of the fits, χ^2_ν , was calculated for the specified fitting ranges. ^(b) Scale factor: multiplier of the spectrum in OMNIFIT (see Eq. A.2). ^(c) The references for the laboratory ice data are [5] Fraser & van Dishoeck (2004), [6] Dawes et al. (2016), [7] Cuppen et al. (2011), and [8] Pontoppidan et al. (2003b).

ice dataset. Further details on the fitting utility can be found in Appendices A.2 and A.3.

Table 3 lists the components and the fit parameters we adopted to fit the VLT-ISAAC data. OMNIFIT was applied in the same way to all the ten SVS 4 sources. To avoid fitting saturated features in the spectra, especially in the 3 μm region, only specific wavelength ranges were considered in the fits. For the *L*-band spectra, the 2.85–2.94 μm , 3.17–3.23 μm and 3.77–4.0 μm ranges were fitted. The first and second of these cover the blue wing and a portion of the red wing of the O-H stretching mode of H₂O ice, respectively. Finally, the third range was included because it was found to be a constraining factor to fit the C-H stretching mode of CH₃OH ice. It is worth noting that the typical C-H stretching region was not selected as a fitting range because of the effect of the 3.47 μm band and the scatter of the red wing of the O-H stretching mode. For the *M* bands, the whole spectral range, 4.62–4.72 μm , was fitted.

The spectral fitting procedure developed by Suutarinen (2015a) and adopted in this study stands as an alternative to the commonly used method to detect molecules in interstellar ices (Grim et al. 1991; Brooke et al. 1999). In contrast to the latter, which consists of fitting a polynomial to the red wing of the O-H stretching mode and analysing the residual optical depth

⁴ <https://ricemunk.github.io/omnifit/>

⁵ <https://lmfit.github.io/lmfit-py/>

Fig. 2. *M*-band optical depth towards the SVS 4 sources (black). The coloured lines represent the CO:CH₃OH 1:1 laboratory spectrum (orange), the CDE-corrected Lorentzian reproducing the pure CO (cyan) and the total fit (magenta). The dashed black lines are used as a reference for $\tau=0$. The goodness of the fit χ^2_ν starting from SVS 4–2 to SVS 4–12 is 0.95, 0.22, 0.79, 0.32, 0.83, 0.74, 0.30, 0.25, 0.87, and 0.64.

at $3.53 \mu\text{m}$ to detect CH₃OH, the fitting procedure we adopted attempts to simultaneously fit multiple ice components to the $3 \mu\text{m}$ region to find the maximum amount of CH₃OH that is hidden below the red wing. This approach makes it possible to concurrently account for both the C-H and the O-H stretches that are attributable to CH₃OH. This aspect is often overlooked, although the O-H stretching contribution of CH₃OH necessarily replaces some of the absorption of H₂O. The aim of this fitting procedure is to determine the maximum amount of CH₃OH ice that is hidden below the red wing of interstellar ices, and thus to help explain the high CH₃OH abundances that are observed in the gas-phase.

Figure 2 shows the optical depth of the sources listed in Table 1 decomposed by analytical and experimental components using the OMNIFIT fitting utility (Suutarinen 2015b). As outlined in Pontoppidan et al. (2003b), the *M*-band features can be decomposed by a linear combination of three components: blue, middle, and red. We address only the middle and red components because the blue component does not constrain the methanol ice abundance, but rather that of CO₂ ice (Boogert et al. 2015). The

central peak (i.e. middle component) is associated with the C-O vibrational mode of pure CO ice. It was fitted using a continuous distribution of ellipsoids (CDE) corrected Lorentzian function in order to take into account irregularities in the grain shape and match the central peak of the observations (Pontoppidan et al. 2003b).

The red component, on the other hand, was fitted with CO:CH₃OH laboratory data (Cuppen et al. 2011) because the observed CO peak position is slightly shifted to longer wavelengths, possibly due to migration of CO in the ices observed towards the cluster sources (Devlin 1992; Zamirri et al. 2018). Although the red component can be associated with CO:H₂O ice (Thi et al. 2006), the CO:CH₃OH mixture is the most likely carrier of this feature (Cuppen et al. 2011), and it is assumed to trace warmer regions than pure CO. The goodness of the fit was addressed using the reduced χ^2_ν , that is given by $\chi^2_\nu = \chi^2/\nu$, where ν is the difference between the number of data points and the number of free parameters in the fit.

The decomposition of the *L*-band features, between 2.80 and $4.15 \mu\text{m}$, was carried out using three experimental components

Fig. 3. *L*-band optical depth towards the SVS 4 sources (black). The coloured lines represent the laboratory ice data employed in the fitting: the pure H₂O (dark blue), the H₂O:CH₃OH 38% (light blue), the CO:CH₃OH 1:1 (orange), and the total fit (magenta). The dashed black lines are used as a reference for $\tau=0$. The cyan boxes illustrate the selected fitting ranges. The goodness of the fit χ^2_v starting from SVS 4–2 to SVS 4–12 is 0.59, 7.47, 0.55, 9.15, 0.79, 4.14, 0.72, 0.43, 0.25, and 22.5.

shown in Fig. 3: pure H₂O in blue (Fraser & van Dishoeck 2004), H₂O:CH₃OH in cyan (Dawes et al. 2016), and CO:CH₃OH in orange (Cuppen et al. 2011). Pure H₂O was selected because it is the most abundant ice component. H₂O:CH₃OH was chosen because CH₃OH is the second major contributor to the O–H stretching at 3 μ m, after H₂O. H₂O:CH₃OH was preferred over pure CH₃OH as the C–H stretching of the latter is too prominent and shifted in the observational data. As Dawes et al. (2016) showed, the O–H spectroscopic profile and exact peak position of the H₂O:CH₃OH mixture are dependent not only on the host molecule of the mixture (H₂O), but also on the minor component (CH₃OH). CH₃OH is thought to form on dust grains from hydrogenation of CO; this may occur early, that is, during the early stages of CH₃OH formation, and involves reactions of HCO + OH, or it may occur late after critical CO freeze-out. Ice studies of binary and tertiary systems show that even if ices form in layers, the heating and processing with time and diffusion will lead to ice mixing. In addition, H₂O:CH₃OH was used because recent modelling and laboratory experiments showed evidence of the production of CH₃OH mixed in H₂O matrices upon UV and X-ray irradiation of simple ice components, for instance,

H₂O:CO (Jiménez-Escobar et al. 2016; Muñoz Caro et al. 2019) or by interaction of CH₄, O₂ and H (Qasim et al. 2018). At the same time, mixtures such as NH₃:H₂O or CO₂:H₂O were discarded because they would have very little effect on the shape and spectroscopy of the O–H stretching at 3 μ m and they would reduce the contribution of CH₃OH, which would prevent us from determining the maximum amount of methanol that is hidden below the red wing. Finally, CO:CH₃OH was selected to ensure that the fit of the methanol band at 3.53 μ m is consistent with the fit of the CO red component of the *M*-band spectra. To do so, the *k* values for CO:CH₃OH obtained in the *M*-band fitting were carried over in the *L*-band fitting. For all the other laboratory ice data, *k* varies. The same approach was also used by Suutarinen (2015a) to fit the *L*-band features of several YSOs, including SVS 4–5 and SVS 4–9. It is worth noting that the 3 μ m water band of SVS 4–12 is saturated (see Fig. A.2), and therefore, the optical depth below $\lambda=3.3$ μ m for this source was determined by scaling the SVS 4–9 *L*-band features to the SVS 4–12 red wing following the procedure presented in Pontoppidan et al. (2004). The best scaling was found for $\tau_{\text{max}}^{L\text{-band}} = 9$.

Table 4. Total ice and gas column densities of the species analysed towards the SVS 4 sources.

Source	$N_{\text{H}_2\text{O}}^{\text{ice}}_{\text{tot}}$ [10^{18} cm^{-2}]	$N_{\text{CO}}^{\text{ice}}_{\text{tot}}$ [10^{18} cm^{-2}]	$N_{\text{CH}_3\text{OH}}^{\text{ice}}_{\text{tot}}$ [10^{18} cm^{-2}]	$N_{\text{CO}}^{\text{gas}}_{\text{tot}}$ [10^{18} cm^{-2}]	$N_{\text{CH}_3\text{OH}}^{\text{gas}}_{\text{tot}}$ [10^{14} cm^{-2}]	$N_{\text{H}_2}^{\text{SCUBA-2}}$ [10^{23} cm^{-2}]	(*) $N_{\text{H}_2}^{\text{AJ}}$ [10^{23} cm^{-2}]
SVS 4–2	1.26 ± 0.11	0.45 ± 0.08	0.22 ± 0.03	$2.71^{+0.55}_{-0.13}$	$8.24^{+12.6}_{-1.70}$	$0.80^{+0.90}_{-0.30}$	0.14
SVS 4–3	3.85 ± 0.32	2.24 ± 0.20	1.06 ± 0.10	$2.58^{+0.53}_{-0.12}$	$1.92^{+1.53}_{-0.10}$	$0.18^{+0.20}_{-0.06}$	0.6
SVS 4–4	1.42 ± 0.09	0.52 ± 0.05	0.28 ± 0.02	$2.65^{+0.53}_{-0.13}$	$3.23^{+2.55}_{-0.13}$	$0.30^{+0.34}_{-0.11}$	0.16
SVS 4–5	5.85 ± 0.60	2.04 ± 0.19	1.91 ± 0.27	$3.70^{+0.75}_{-0.18}$	$4.50^{+6.80}_{-0.87}$	$0.65^{+0.73}_{-0.24}$	0.7
SVS 4–6	1.38 ± 0.17	0.70 ± 0.08	0.52 ± 0.06	$3.20^{+0.65}_{-0.16}$	$6.67^{+10.2}_{-1.29}$	$0.78^{+0.87}_{-0.28}$	0.16
SVS 4–7	3.40 ± 1.00	1.10 ± 0.09	0.98 ± 0.64	$2.80^{+0.57}_{-0.14}$	$3.27^{+4.98}_{-0.59}$	$0.16^{+0.18}_{-0.06}$	0.35
SVS 4–8	2.06 ± 0.14	1.36 ± 0.07	0.64 ± 0.05	$2.77^{+0.56}_{-0.14}$	$3.10^{+2.44}_{-0.14}$	$0.20^{+0.22}_{-0.07}$	0.36
SVS 4–9	1.91 ± 0.14	2.06 ± 0.37	1.26 ± 0.11	$2.35^{+0.48}_{-0.11}$	$2.17^{+2.72}_{-0.32}$	$0.28^{+0.32}_{-0.10}$	0.35
SVS 4–10	1.46 ± 0.07	1.16 ± 0.03	0.57 ± 0.06	$2.66^{+0.54}_{-0.13}$	$2.81^{+2.81}_{-0.27}$	$0.38^{+0.42}_{-0.14}$	0.2
SVS 4–12	12.4 ± 5.90	3.12 ± 0.74	2.28 ± 0.18	$3.32^{+0.68}_{-0.16}$	$3.14^{+4.77}_{-0.60}$	$0.73^{+0.82}_{-0.26}$	0.86

Notes. Columns 5–7 list the column densities that were calculated for $T = 15$ K. For $N_{\text{CO}}^{\text{gas}}$, $N_{\text{CH}_3\text{OH}}^{\text{gas}}$, and N_{H_2} , the values in the superscript and subscript represent the upper and lower limits if the column densities are calculated at $T = 10$ K or $T = 20$ K, respectively. (*) Estimated relative uncertainty of 5%. See Sects. 3.1–3.2 and Appendices A, B, and C for a more detailed description of the determination of ice, gas, and H_2 column densities.

Despite the degeneracies involved in the spectral fitting, Fig. 3 shows that in addition to the contribution of the O-H stretching of methanol, the pure H_2O component mainly reproduces the $3 \mu\text{m}$ absorption band. This is in agreement with a scenario where the predominant ice constituent is pure water, but it also supports the hypothesis of a degree of mixing in astrophysical ices. For most of the spectra, a third component, the $\text{H}_2\text{O}:\text{CH}_3\text{OH}$ mixture, is required to obtain a better fit constrained by the adopted fitting ranges. For some sources, for example SVS 4–2, SVS 4–4, and SVS 4–6, the selection of the fitting ranges results in an overfit of the O-H stretching mode. Given the low signal-to-noise ratio (S/N) of the observations, this study does not aim to prove that $\text{H}_2\text{O}:\text{CH}_3\text{OH}$ models the observational spectra better than other laboratory data. It was selected to find the maximum amount of CH_3OH that is hidden in the H_2O ice, if the L band is decomposed with the laboratory data selected in this study.

It is worth noting that the CH_3OH band at $3.53 \mu\text{m}$ is not constrained by the fitting procedure itself, but rather by the methanol fraction in both $\text{CO}:\text{CH}_3\text{OH}$ and $\text{H}_2\text{O}:\text{CH}_3\text{OH}$ mixtures. The amount of CH_3OH estimated from the M -band fitting results in sufficient absorption to model the C-H stretching mode at $3.53 \mu\text{m}$, and therefore the addition of $\text{H}_2\text{O}:\text{CH}_3\text{OH}$, aimed to fit the constrained ranges, has a minor contribution in the 3.3 – $3.6 \mu\text{m}$ interval. The only two exceptions are SVS 4–3 and SVS 4–5 for which a greater contribution of the $\text{H}_2\text{O}:\text{CH}_3\text{OH}$ mixture is observed. Overall, the fit of the C-H stretching mode at $3.53 \mu\text{m}$ is satisfactory because the model is predicting an absorption lower than or equal to the observed band, as well as taking into account that other molecules and physical processes, such as scattering by large grains, contribute to this spectral range. Reproducing the full range of absorptions observed in the red wing was not part of the scope of this study, and the selected fitting ranges would indeed prevent a good quality fit of it.

The CO, H_2O , and CH_3OH ice column densities were obtained from the integrated τ of the components found by the fitting routine. The calculation of the ice column densities is described in detail in Appendices A.3–A.4 and their values are shown in Tables 4 and 5. In these tables, the total ice column

Table 5. Ice column densities of the pure and mixed components given as percentages of the total column densities.

Source	$\frac{N_{\text{H}_2\text{O}}^{\text{ice}}_{\text{pure}}}{N_{\text{H}_2\text{O}}^{\text{ice}}_{\text{tot}}} [\%]$	$\frac{N_{\text{CO}}^{\text{ice}}_{\text{pure}}}{N_{\text{CO}}^{\text{ice}}_{\text{tot}}} [\%]$	$\frac{N_{\text{CH}_3\text{OH}}^{\text{ice}}_{\text{in H}_2\text{O}}}{N_{\text{CH}_3\text{OH}}^{\text{ice}}_{\text{tot}}} [\%]$
SVS 4–2	89.7 ± 11.7	62.2 ± 21.7	22.7 ± 13.9
SVS 4–3	62.1 ± 8.50	73.2 ± 11.6	43.4 ± 9.43
SVS 4–4	84.5 ± 8.30	50.0 ± 11.7	7.10 ± 3.61
SVS 4–5	26.3 ± 6.56	65.2 ± 11.7	62.8 ± 16.3
SVS 4–6	89.9 ± 16.0	42.9 ± 11.7	23.1 ± 9.98
SVS 4–7	91.2 ± 39.8	88.2 ± 11.5	89.8 ± 87.8
SVS 4–8	91.3 ± 8.84	55.9 ± 5.51	6.20 ± 1.64
SVS 4–9	97.9 ± 10.3	42.2 ± 20.7	5.6 ± 3.21
SVS 4–10	98.6 ± 6.73	58.6 ± 2.65	15.8 ± 10.7
SVS 4–12	97.7 ± 66.3	27.3 ± 23.9	0.40 ± 0.44

Notes. To avoid redundancy, the percentages of ice column densities of H_2O in CH_3OH , CO in CH_3OH , and CH_3OH in CO w.r.t. the total H_2O , CO, and CH_3OH ice column densities are not tabulated. They are equal to 100 minus the value reported in the corresponding column (e.g. 10.3 cm^{-2} for H_2O in CH_3OH towards SVS 4–2). See Sect. 3.1 and Appendix A for a more detailed description of the determination of ice column densities.

density is the sum of the pure and mixed components. SVS 4–12 shows the deepest absorptions features, thus the column densities are the highest towards this source. The uncertainties in the column density were calculated from the error in the optical depth.

Figure 4 compares the derived ice column densities between the SVS 4 sources (Table 4) to measurements from the literature (Pontoppidan et al. 2004; Suutarinen 2015a). Because of the low S/N, SVS 4–12 is not included in this figure. In the case of H_2O ice, shown in the upper panel, the pure water component is the most abundant compared to the mixed water, except in the case of SVS 4–7. This result indicates a negligible level of molecular migration in the ice matrix. It is also worth observing that the H_2O ice column density is diminished by the contribution of the

Fig. 4. H₂O (*top*), CO (*middle*), and CH₃OH (*bottom*) ice column densities obtained in this study compared to Pontoppidan et al. (2004) (light grey) and Suutarinen (2015a) (dark grey). The CO column density towards SVS 4–10 is from Chiar et al. (1994). The coloured bars represent the ice column densities of the pure species or of the species in a mixture, and the dashed bars depict the total ice column densities obtained by summing the ice column densities of the pure species and of the species in a mixture.

O–H stretching associated with CH₃OH. In the case of CO ice, the pure CO column density dominates the mixed component, except in the case of SVS 4–4, SVS 4–6 and SVS 4–9, which suggests that the circumstellar environment around these three objects is warmer than in the other regions in the SVS 4 cluster. In one case, SVS 4–4, the column densities of pure CO and CO in the CO:CH₃OH mixture are the same.

For CH₃OH, the CO:CH₃OH component dominates in all the sources, except for SVS 4–5 and SVS 4–7. This indicates that the amount of methanol constrained from the *M*-band fitting is sufficient to reproduce the methanol absorption in the *L* band. SVS 4–4 shows the same behaviour as observed in the CO case because the column densities of CH₃OH in CO:CH₃OH and H₂O:CH₃OH are the same. When the values estimated in this study can be compared to the literature, the total ice methanol column densities agree well with those reported by Pontoppidan et al. (2004), except for SVS 4–9 because of uncertainties in the local continuum determination for this particular source.

SVS 4–5 has the highest methanol column density in both studies except for SVS 4–12. The column densities given by Suutarinen (2015a) are generally a factor of ~ 1 – 3 lower. The average total ice column densities of H₂O, CO, and CH₃OH are $2.5 \times 10^{18} \text{ cm}^{-2}$, $1.3 \times 10^{18} \text{ cm}^{-2}$, and $0.8 \times 10^{18} \text{ cm}^{-2}$, respectively. The CO and CH₃OH average abundances with respect to H₂O are 0.52 and 0.32. The high CO fraction relative to H₂O indicates an environment for the SVS 4 cluster with a temperature below the CO desorption (~ 20 K), and it agrees with the average ice column densities of low-mass stars shown in Öberg et al. (2011a). On the other hand, the CH₃OH fraction with respect to H₂O ice is a factor of 2.6 higher than the upper quartile values calculated in Öberg et al. (2011a). Nevertheless, this value is consistent with the high methanol ice abundance for the SVS 4 cluster measured by Pontoppidan et al. (2004), namely 0.28, which suggests a peculiar efficiency of methanol ice synthesis in this region of the Serpens molecular core.

3.2. Gas column densities

The CO isotopologue and CH₃OH gas column densities were calculated from the integrated line intensities from the combined SMA + APEX maps. Table 2 lists the spectral line data of the detected molecular transitions. All the gas column densities derived in this section and their uncertainties are listed in Table 4, and the CO and CH₃OH column density maps are displayed in Fig. 5. Towards some of the SVS 4 sources, the ¹³CO emission is found to be moderately optically thick (see Appendix B.2). As a result, the ¹³CO column densities are underestimated towards these positions. Therefore, the optically thin C¹⁸O emission is used to estimate the column density of the CO gas. The C¹⁸O column densities are obtained using the combined SMA + APEX integrated intensity of the C¹⁸O $J = 2$ – 1 line at 219.560 GHz, assuming a kinetic temperature equal to 15 K and optically thin emission. The derived C¹⁸O column densities are of the order of 10^{15} cm^{-2} towards all the SVS 4 star positions. The C¹⁸O column densities are then converted into ¹²CO column densities using a ¹⁶O/¹⁸O isotope ratio of 557 ± 30 (Wilson 1999). The calculated ¹²CO column densities are of the order of 10^{18} cm^{-2} towards the SVS 4 stars (Fig. 5).

The gas column densities of CH₃OH towards the SVS 4 sources were calculated from the combined SMA + APEX integrated intensities by assuming local thermodynamic equilibrium (LTE) and that the emission of methanol is optically thin. A kinetic temperature equal to 15 K was selected in this case as well, representing the global temperature of the cluster (see Sect. 4.1). The measured CH₃OH column densities are of the order of 10^{14} cm^{-2} towards all the SVS 4 sources (Fig. 5). Similar column densities are also reported in Kristensen et al. (2010), especially towards two outflow knot positions nearby SMM 4 labelled SMM 4–S and SMM 4–W and in Öberg et al. (2009) towards SVS 4–5. In case of sub-thermal excitation, the methanol column density would be overestimated by up to one order of magnitude (Bachiller et al. 1995, 1998).

4. Analysis

4.1. H₂ column density and physical structure of the region

The SVS 4 sources might be embedded within the envelope of SMM 4 to different degrees and not be uniformly located behind it (Pontoppidan et al. 2004). As a result, the absolute ice column densities might not be the most appropriate measure to compare directly to gas-phase column densities. The gas and ice

Fig. 5. Gas column density maps of the SVS 4 cluster. *a*: ^{12}CO column density map. *b*: CH_3OH column density map. The white spaces within the area covered by SMA+APEX are regions where the strength of the emission drops below 5σ . The red crosses mark the position of the SVS 4 sources, and the white star represents SMM 4.

observations might be tracing different columns of material. To address this point, a search for an ice-gas correlation was conducted by comparing gas and ice abundances relative to the H_2 column density of the region. The abundances of the gas species were calculated by dividing the gas column densities by the H_2 column density estimated from the submillimetre continuum (SCUBA-2) map at $850\ \mu\text{m}$ (Herczeg et al. 2017), assuming that the continuum radiation comes from optically thin thermal dust emission (Appendix C and Kauffmann et al. 2008). Under these assumptions, the strength of the submillimetre continuum emission depends on the dust temperature, T , on the column density, and on the opacity, κ_v .

The dust temperature for the SVS 4 region has previously been estimated to lie in the range of $10\ \text{K} \leq T \leq 20\ \text{K}$ according to Schnee et al. (2005) and to the dust radiative transfer model presented in Kristensen et al. (2010). The H_2 column density is thus calculated for $T = 10\ \text{K}$, $15\ \text{K}$ and $20\ \text{K}$. We adopted the opacities corresponding to dust grains covered by a thin ice mantle (Ossenkopf & Henning 1994) with κ_v equal to $0.0182\ \text{cm}^2\ \text{g}^{-1}$ at $850\ \mu\text{m}$ (“OH5 dust”). When a temperature of $15\ \text{K}$ is assumed, all the sources lie in the region where the H_2 column density is of the order of $10^{22}\ \text{cm}^{-2}$ (see Fig. C.1 and Table 4). The estimated gas abundances relative to H_2 range from 10^{-5} – 10^{-4} for CO and 10^{-9} – 10^{-8} for CH_3OH at the SVS 4 source positions. The latter agree with the values measured by Kristensen et al. (2010) towards the Serpens molecular core.

The H_2 column densities derived from the SCUBA-2 measurements using the method above provide a good estimate of the total beam-averaged amount of gas and are therefore useful as a reference for the optically thin gas-phase tracers. However, it is not clear that they can directly be related to the ice data that provide (pencil-beam) measurements of the column densities towards the infrared sources that may or may not be embedded within the cloud. For the ice abundances we therefore adopted a slightly different method of deriving the H_2 column densities, starting from the extinction in the J -band A_J (Table 1) and adopting the relation $N_{\text{H}_2} = 3.33 \times 10^{21} A_J$ given in Fig. 10 of Pontoppidan et al. (2004). At the SVS 4 source positions, the H_2 column density is of the order of $10^{22}\ \text{cm}^{-2}$ and the measured ice abundances relative to H_2 are of the order of 10^{-5} for CO and CH_3OH and 10^{-5} – 10^{-4} for H_2O ice. The ice abundances agree with the values reported by Pontoppidan et al. (2004) for the SVS 4 cluster. The column densities derived using the two

Fig. 6. H_2 column density estimated from the $850\ \mu\text{m}$ dust emission map (Herczeg et al. 2017) as a function of the distance from SMM 4. A distance of $433\ \text{pc}$ is assumed (Ortiz-León et al. 2018) in order to show the distance in astronomical units. All the sources are located in both CO and CH_3OH freeze-out zones, as indicated by the solid arrows and the grey dashed line, as taken from the DUSTY model in Kristensen et al. (2010).

different methods are of the same order of magnitude, but with small variations, possibly due to the assumptions about the temperature, the exact location of the infrared sources along the LoS compared to the distribution of the cloud material, and the differences in the exact column densities traced by the SCUBA-2 and A_J measurements.

Figure 6 shows the N_{H_2} variation as a function of the distance from the SMM 4 position for each SVS 4 source. The upper and lower error bars in this figure represent the H_2 column density calculated for $T = 10\ \text{K}$ and $20\ \text{K}$, respectively. The vertical dashed line indicates the dust temperature of $20\ \text{K}$ at $1500\ \text{AU}$ from SMM 4, calculated from Kristensen et al. (2010) by scaling the luminosity of the protostar according to the most updated distance measurements obtained with *Gaia*-DR2 ($433\ \text{pc} \pm 4$; Ortiz-León et al. 2018). The DUSTY model assumes a spherically symmetric envelope and that the central heating source is a blackbody at $T = 5000\ \text{K}$. The black rightward arrow indicates the distance where CO gas is expected to freeze out on dust grains, which enhances the CH_3OH formation through CO

hydrogenation. Pure CO ice starts to desorb at $T > 20$ K (black leftward arrow), although some frozen CO molecules migrate to porous water ice and are only desorbed at $T > 90$ K (Collings et al. 2003). According to the model, the methanol ice desorption region is located below 50–100 AU, as indicated by the solid grey arrow in the figure. The comparison with the model shows that the SVS 4 sources lie in a region in which both CO and CH₃OH are frozen out. The observed gas emission associated with these molecules, however, has been released to the gas-phase by non-thermal desorption mechanisms.

4.2. Combined gas-ice maps

Figures 7a and b compare the CO ice abundance to the gas-phase ¹³CO 2–1 (panel a) and C¹⁸O 2–1 (panel b) emission. Because of optical depth effects, the C¹⁸O emission shows more structure than ¹³CO and traces the densest regions of the cluster. The interplay between CO ice and CO gas in cold dark regions is mainly dominated by the freeze-out of CO gas onto the dust grains. When we assume that the overall column density of CO molecules (CO gas + CO ice) is constant, an anti-correlation is expected to be observed between CO gas and CO ice. Most of the SVS 4 sources show higher CO ice abundances (e.g. SVS 4–6, SVS 4–9, and SVS 4–10) where the ¹³CO emission is more intense, suggesting that part of the variations are due to the overall physical structure of the region. The same relations are seen in panel b. Because ice absorption and gas emission might not be probing the same column of material, this preliminary conclusion has to be verified by comparing ice and gas abundances, and this is addressed in Sect. 4.3.

To test whether the C¹⁸O line emission traces the densest regions of the core, Fig. 8 shows a comparison of the 850 μ m dust continuum distribution in SVS 4 with molecular emission traced by C¹⁸O. It can be observed that the C¹⁸O emission in SVS 4 does not closely follow the dust emission. However, some care has to be taken in interpreting the dust emission map of SVS 4 because embedded sources can lead to an increase in dust temperature, and consequently, in the submillimetre continuum flux, which alters the dust emission morphology (e.g. Chandler & Carlstrom 1996). Still, the distributed C¹⁸O emission does indicate that CO gas is present on larger scales in the outer envelope of SMM 4.

Figures 7c and d compare the CH₃OH ice (panel c) and H₂O ice (panel d) abundances to the CH₃OH 5₀–4₀ A⁺ integrated intensity. The peak CH₃OH emission likely traces the emission of the outflow associated with SMM 4 (Kristensen et al. 2010): the strongest CH₃OH emission is observed in three ridges in the NW/SE direction from the centre of the cluster and not where the majority of the SVS 4 sources are located. Two ridges are localised in the vicinity of SMM 4, and the third is observed in the southern region of the map, in the proximity of the outflow knot position SMM 4–S. No straightforward trend is observed between gas-phase methanol and water ice: generally, the H₂O ice abundances are higher where the gas-phase methanol emission is stronger (e.g. SVS 4–2, SVS 4–5, SVS 4–6, and SVS 4–12). Similarly, the methanol ice abundances are lower where the methanol emission is weaker (e.g. SVS 4–4, SVS 4–8). However, some deviations from this behaviour are seen for SVS 4–2, SVS 4–7, and SVS 4–10.

It is worth noting that the morphology of the CH₃OH emission differs from the emission of the CO isotopologues. While the CH₃OH emission is structured, the CO isotopologues show a more uniform distribution. Furthermore, the emission of each molecular tracers is very much dominated by the large-scale

Fig. 7. Gas-ice maps of the SVS 4 cluster. Ice abundances are shown as black circles. The contours at 3σ , 6σ , 9σ , etc. represent the gas-phase integrated intensities. *a*: CO abundances on gas ¹³CO 2–1; *b*: CO abundances on gas C¹⁸O 2–1; *c*: CH₃OH abundances on gas CH₃OH 5₀–4₀ A⁺. *d*: H₂O abundances on gas CH₃OH 5₀–4₀ A⁺. The white crosses mark the position of the SVS 4 sources, and the white star represents SMM 4.

structure of SMM 4 and no separate peaks are seen towards any of the SVS 4 sources, suggesting that they do not strongly affect the gas locally.

4.3. Gas and ice variations

To further explore trends between ice and gas in the region, Fig. 9 compares the inferred values towards each of the SVS 4 cluster

Fig. 8. *a*: SCUBA-2 850 μm dust continuum emission (contours decrease in steps of 10% starting at 3120 mJy beam $^{-1}$, Herczeg et al. 2017). *b*: integrated intensity from the molecular emission line of C ^{18}O 2–1 (contours are at 3σ , 6σ , 9σ , etc.). The white crosses mark the position of the SVS 4 sources, and the white star represents SMM 4.

members. Figure 9a shows that there is no clear trend between CO ice and ^{12}CO gas column densities. For instance, the CO gas column density for SVS 4–3 and SVS 4–4 changes only by 3%, whereas the ice column density for these sources changes by a factor of 4.3. The ^{12}CO gas column density is almost uniform at the SVS 4 source positions, suggesting an extended gaseous component that is not sensitive to CO freeze-out. As discussed in Sect. 4.2, an anti-correlation between CO ice and gas is expected in cold dark star-forming regions due to the effect of CO freeze-out. The absence of this trend in SVS 4 indicates that this relation is not valid in this region, which is characterised by a complex physics. The low temperatures in the cluster allow CO freeze-out to occur, but at the same time, due to temperature variations and dust heating around 20 K caused for example by SMM 4 or its outflow, the frozen CO is efficiently released into the gas phase.

Figure 9b compares the CH $_3\text{OH}$ gas and ice column densities. The CH $_3\text{OH}$ gas map in Fig. 5b indicates that the methanol column density is higher around SMM 4 and just south of SVS 4–7; it is almost one order of magnitude higher than towards the column density at the SVS 4 source positions. Figure 9b shows that the gas column density spans from ~ 1.9 to 8×10^{14} cm $^{-2}$ and the ice column density from ~ 0.2 to 2.3×10^{18} cm $^{-2}$. The dashed grey line illustrates the sources that are located within 9000 AU from SMM 4. The sources in the vicinity of SMM 4, excluding SVS 4–12, show an enhancement in the CH $_3\text{OH}$ gas column density of a factor of 1.5–3.0, in agreement with strong methanol emission associated with the SMM 4 outflow. SVS 4–12, a particularly deeply embedded source ($A_V = 26$ mag), does not follow this trend. On the other hand, no clear enhancement of the methanol ice column densities is seen in the SMM 4 outflow region. It thus appears that the majority of the methanol is in solid form on the grains, even for the LoSs showing gas methanol enhancements.

Figures 9a and b show that the chemical behaviours of CH $_3\text{OH}$ and CO are anti-correlated: larger variations are observed for CH $_3\text{OH}$ gas than for CH $_3\text{OH}$ ice, while the opposite is seen for CO. This might be partly explained by the higher volatility of CO compared to CH $_3\text{OH}$, especially because the temperatures in the cluster are close to the CO sublimation temperature (15–20 K).

The CO and CH $_3\text{OH}$ gas column density are compared to the H $_2\text{O}$ ice column density in panels c and d, although no

correlation is expected between them because their formation routes are different. The column density of water ice varies from ~ 1.3 to 5.9×10^{18} cm $^{-2}$ when SVS 4–12 is not taken into account. SVS 4–12 shows an additional enhancement of a factor of 2. The large error bars for this source are due to the low S/N in the *L* and *M* bands and the poor fitting in the red wing between 3.0 and 3.7 μm . Such a high variation indicates that this region is cold to keep water in the solid phase, and that simultaneously, the hydrogenation of atomic oxygen to form water occurs efficiently. The same trends observed in panels a and b are also seen when CO and methanol gas are compared to H $_2\text{O}$ ice.

Figures 9e–h illustrate the gas and ice abundances towards the cluster. A lack of correlation between the ice and gas species is also observed when the relative abundances are compared. This additional result supports the conclusion that there is no straightforward correlation between CO and CH $_3\text{OH}$ gas with their ice counterparts in the cluster. This is most likely related to the complexity of the SVS 4 morphology: the presence of the Class 0 protostar and its envelope, the outflow that intersects the cluster, and the vicinity of the SVS 4 stars. All these factors are reflected in temperature and density variations throughout the entire region.

5. Discussion

In the previous sections, gas-ice maps have been analysed to investigate the feedback between ice and gas processes. In this section, the information contained in the maps is used to directly determine the CH $_3\text{OH}$ and CO gas-to-ice ratios ($N_{\text{gas}}/N_{\text{ice}}$) shown in Fig. 10, calculated from the column densities derived in Sects. 3.1 and 3.2. The azure shaded areas in the figure indicate the estimated ranges of CH $_3\text{OH}$ and CO gas-to-ice ratios towards the SVS 4 sources, whereas the dotted light blue line displays the CH $_3\text{OH}$ gas-to-ice ratio estimated by Öberg et al. (2009). The solid black lines show the predictions from the astrochemical model by Cazaux et al. (2016): the model simulates a typical molecular cloud with a three-phase chemical model that includes gas-phase chemistry that interacts with the surface and bulk chemistry. In the model, thermal desorption and non-thermal desorption of the species in the ice mantles are taken into account. More specifically, two non-thermal desorption mechanisms are included for CO and H $_2\text{O}$: (i) absorption of a single

Fig. 9. Gas and ice variations. *Panels a–d:* relation between CO, CH₃OH, and H₂O ice and CO and CH₃OH gas column densities. *Panels e–h:* relation between CO, CH₃OH, and H₂O ice and CO and CH₃OH gas abundances relative to H₂. The coloured filled circles identify the SVS 4 stars; the dashed grey line divides the sources into two groups: YSOs located within 9000 AU from SMM 4, and YSOs located at distances >9000 AU from SMM 4.

UV-photon or induced by H₂ ionisation by cosmic rays (i.e. photodesorption), and (ii) desorption promoted by the exothermicity of a chemical reaction (i.e. reactive desorption). The CH₃OH ice-to-gas ratio found by Cazaux et al. (2016) agrees very well with the lower value derived in this study. It is important to note that only one non-thermal desorption mechanism for methanol

is included in the model, reactive desorption. This keeps the gas-to-ice ratio at about 10^{-4} . If additional non-thermal desorption mechanisms were considered, the methanol gas-to-ice ratio calculated by the model would be higher.

The CH₃OH gas-to-ice ratio ($N_{\text{CH}_3\text{OH}_{\text{gas}}}/N_{\text{CH}_3\text{OH}_{\text{ice}}}$) varies between 1.4×10^{-4} and 3.7×10^{-3} (Fig. 10a). The higher values

Fig. 10. CH₃OH and CO gas-to-ice ratios ($N_{\text{gas}}/N_{\text{ice}}$) for the SVS 4 sources in the Serpens molecular core. The shaded azure areas represent the ranges estimated in this paper for both molecules. The curves represented by the solid black lines indicate the theoretical ratio estimated from the astrochemical model by Cazaux et al. (2016). The dashed light blue line in the left panel marks the ratio estimated by Öberg et al. (2009).

correspond to SVS 4–2 and SVS 4–6, which are located at the CH₃OH peak emission close to SMM 4. These two sources also show the highest CH₃OH gas column densities. Non-thermal desorption mechanisms might be more efficient in this region of the cluster because of the higher degree of UV irradiation originating from the SMM 4 protostar.

The lower values reflect the less efficient methanol non-thermal desorption of the protostars located farther away from SMM 4, and that are by inference subjected to a lower degree of UV irradiation. Simultaneously, because the SMM 4 outflow intersects the cluster, gas-phase destruction by shocks (e.g. collisional dissociation) might be responsible for low gas-to-ice ratios in the region. Our derived value is supported by previous measurements by Öberg et al. (2009) towards four embedded Class 0/I low-mass protostars.

The CO gas-to-ice ratio ($N_{\text{CO}_{\text{gas}}}/N_{\text{CO}_{\text{ice}}}$) derived in this study varies between 1 and 6 (Fig. 10b). This range is significantly higher than the one predicted in the model by Cazaux et al. (2016). As discussed previously in Sect. 4, according to the DUSTY model calculated for SMM 4 in Kristensen et al. (2010), the dust temperature in the SVS 4 cluster is estimated to be below 20 K, and at these temperatures, CO is indeed expected to be frozen out on grains. The high relative abundance of gaseous CO might be attributed to the morphology of the SVS 4 cluster, and more specifically, to the extended gaseous component traced in the CO gas observations. Because this component is not included in the model by Cazaux et al. (2016), this explains the mismatch found in Fig. 10b.

6. Conclusions

We presented SMA and APEX observations of Serpens SVS 4, a dense cluster of low- to intermediate-mass young stars located in the outer envelope of the Class 0 protostar SMM 4. The SMA observations were combined with APEX single-dish maps and with data from the VLT archive to construct combined gas-ice maps of H₂O, ¹²CO and CH₃OH of the cluster. In these maps the abundances of H₂O, ¹²CO, and CH₃OH ices relative to H₂ are displayed with the gas-phase emissions of CH₃OH, ¹³CO, and C¹⁸O. These suites of maps are powerful probes of the physical and chemical history of dense cores. They allowed us to study the complex relationships between gas and ice, specifically, the processes linking ice to gas-phase density in cold dark regions: freeze-out and non-thermal desorption. Finally, gas-to-ice ratios of CO and CH₃OH were directly measured to observationally validate their theoretical predictions. The main conclusions of the paper are summarised below.

CO gas and H₂ do not follow the same density profile. The H₂ column density increases from SW towards SMM 4, whereas the

CO ridge is located at the centre of SVS 4 cluster. Nevertheless, both distributions are more uniform than that of CH₃OH, which shows three strong ridges that are likely associated with the sputtering induced by the SMM 4 outflow. The methanol gas column density in these regions is around one order of magnitude higher than that at the SVS 4 source positions.

There is no clear trend between CO and CH₃OH gas with their ice counterparts in the SVS 4 cluster. This result is expected based on the physical structure of the SVS 4 cluster. Temperature and density variations that affect the chemistry are present in the region, which is strongly influenced by the Class 0 protostar, its outflow, and the high YSO density. The CH₃OH and CO chemical behaviours are anti-correlated: larger variations are seen for CH₃OH gas than for CH₃OH ice, while the opposite is seen for CO.

The CO gas-mapping illustrates the existence of an extended gaseous component that does not probe the densest regions of the cluster where the ice is located. Consequently, the effect of the freeze-out on the CO gas column densities is not observed. This is reflected in higher CO gas column densities and in higher CO gas-to-ice ratios compared to the theoretical ratio estimated by Cazaux et al. (2016).

The higher values for the CH₃OH gas-to-ice ratio, induced by the sources located close to the SMM 4 ridges, agree well with the prediction that methanol ice can be formed on dust grains by surface chemistry and is then released into the gas phase in cold regions through non-thermal desorption. The lower values match the measurements performed by Öberg et al. (2009) for embedded Class 0/I low-mass protostars. Generally, the methanol gas-to-ice ratio range found in this study promotes a scenario in which the vast majority of the methanol molecules in SVS 4 is in ice form, condensed on the surfaces of dust grains.

Similar studies of other star-forming regions will reveal how universal, for example, the gas-to-ice ratios and trends found for the Serpens SVS 4 cluster are. For example, more isolated young stellar objects are suitable to address how efficiently methanol is desorbed in absence of external irradiation. In contrast, regions dominated by strong external irradiation can constrain how efficient the methanol photodesorption is compared to the other non-thermal desorption mechanisms. Future observations with the *James Webb* Space Telescope (JWST) will overcome the main limitation in the detection of complex molecules in the ice phase, the low spectral resolution. For example, medium-resolution MIRI observations of the 7–8 μm region will allow us to access the ice content of a suite of species more complex than methanol (e.g. CH₃CHO and CH₃CH₂OH). The combination of these data with high-sensitivity ALMA observations will enable us to construct accurate gas-ice maps of several complex organic molecules and to distinguish the interplay between ice and gas in low- and high-mass star-forming regions.

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Appendix A: Fitting of ice data

A.1. Continuum determination

In order to derive the column densities of ice water, carbon monoxide, and methanol, the *L*- and *M*-band spectra have to be converted into an optical depth scale given by

$$\tau_\lambda = -\ln\left(\frac{F_\lambda^{\text{obs}}}{F_\lambda^{\text{cont}}}\right), \quad (\text{A.1})$$

where F_λ^{obs} is the observed flux and F_λ^{cont} is the continuum spectral energy distribution (SED).

Determining the continuum of embedded sources is not straightforward because several physical parameters of the disc and envelope must be known (Whitney et al. 2003; Gramajo et al. 2010; Robitaille 2017), together with accurate photometric measurements. In this paper, the continuum of the *L*-band observations was derived by the fitting of the near-infrared photometric data in Table A.1 and the spectral data above $3.6 \mu\text{m}$. The accuracy of the 2MASS photometric data and VLT-ISAAC spectral data is about 8% and 13%, respectively. To account for the different flux accuracy, weighted fits were used to determine the continuum: less weight was given to the VLT data compared to 2MASS data. The weights are inversely proportional to the variance of the data. The fitting was performed using one or two blackbodies if A_J towards the source was higher or lower than 9.8 mag, respectively. Although a huge degeneracy involving the disc (M_{disc}) and envelope mass (M_{env}) and the inclination (i) arises in interpreting SED of YSOs, the use of one blackbody to trace the continuum of the *L*-band observations towards embedded sources ($M_{\text{env}} \sim 0.4 M_\odot$), as result of the re-emission of the stellar flux by the envelope, is consistent with radiative transfer models (Whitney et al. 2003; Robitaille et al. 2006, 2007) of Class 0 and late Class 0 objects. In less embedded environments, the combination of the scattered or re-emitted photons by the disc and envelope becomes more evident, and a low-infrared excess is observed longward of $3.6 \mu\text{m}$. In this case, a second blackbody component is required to fit the final part of the *L* band. Two blackbodies were adopted for SVS 4–5 because of the high mid-infrared excess, as pointed out by Pontoppidan et al. (2004), and because SVS 4–9 is a peculiar source due to its strong X-ray flux (Preibisch 2003). Because the extinction law at the *L* bands is significantly lower than the visual extinction (Cardelli et al. 1989), we decided to use reddened blackbody functions as also adopted by previous studies (Ishii et al. 2002; Chiar et al. 2002; Moutaka et al. 2004). The good agreement between the optical depths of the SVS 4 sources obtained in this work and those derived by Pontoppidan et al. (2004, see their Figs. 4–6 and A.1 and A.2 of this work) contributes to the reliability of this method. The left-hand sides of Figs. A.1 and A.2 show the observed flux, the photometry data, and the synthetic continuum used in this paper. The optical depth, calculated with Eq. (A.1), is shown on the right-hand side of both figures. SVS 4–12 is a saturated source, and only the red wing is shown. In order to estimate the optical depth, the SVS 4–9 curve was scaled to the red wing of SVS 4–12, as suggested by Pontoppidan et al. (2004). The authors stated that the optical depth profile does not change significantly if another SVS 4 source is used in the scaling because the SVS 4 spectra have similar shapes.

For the *M*-band observations, on the other hand, the local continuum was calculated with a spline function. In order to only take the continuum SED into account, the CO and ^{13}CO 1–0 ro-vibrational transitions were masked together with the Pfund HI

Table A.1. Photometry of the SVS 4 sources.

SVS	1.235 $\mu\text{m}^{(a)}$ [mJy]	1.250 $\mu\text{m}^{(b)}$ [mJy]	1.635 $\mu\text{m}^{(b)}$ [mJy]	1.662 $\mu\text{m}^{(a)}$ [mJy]	2.159 $\mu\text{m}^{(a)}$ [mJy]
4–2	1.59 ± 0.08	1.8 ± 0.2	8.5 ± 0.9	7.73 ± 0.25	16.4 ± 0.38
4–3	≤ 0.09	–	0.4 ± 0.1	≤ 0.24	1.59 ± 0.08
4–4	1.37 ± 0.06	1.50 ± 0.2	10.5 ± 1	10.5 ± 0.3	24.5 ± 0.56
4–5	≤ 0.4	–	0.03 ± 0.01	≤ 2.34	4.0 ± 0.3
4–6	0.6 ± 0.06	0.5 ± 0.1	3 ± 0.3	3.19 ± 1.62	10.3 ± 0.49
4–7	≤ 0.08	0.015 ± 0.005	0.6 ± 0.1	0.48 ± 0.08	4.3 ± 0.13
4–8	≤ 0.21	0.04 ± 0.01	1.8 ± 0.2	1.76 ± 0.10	14.4 ± 0.37
4–9	≤ 0.38	0.21 ± 0.05	9.7 ± 0.1	10.1 ± 0.39	68.6 ± 2.15
4–10	0.79 ± 0.07	0.6 ± 0.1	9.9 ± 1	10.7 ± 0.44	41.4 ± 1.0
4–12	–	–	–	–	0.2 ± 0.02

Notes. ^(a)From 2MASS (Skrutskie et al. 2006). ^(b)From UKRIT (Pontoppidan et al. 2004).

line. To perform the masking, the CO and ^{13}CO ro-vibrational spectra obtained from HITRAN database⁶ (Rothman et al. 1987) were overlaid on the SEDs. The narrow gas-phase lines were then carefully removed from the SEDs at the designated frequencies.

A.2. Optical depth fitting

The *M*-band optical depths were fitted using the OMNIFIT code (Suutarinen 2015b), an open-source code that aims to fit observational data of astrophysical ices using multi-component laboratory spectra and analytical data. The LMFIT package⁷ was used to perform non-linear optimisation with the Levenberg-Marquardt method. *M*-band optical depths were modelled by combining a CDE-corrected Lorentzian function CO:CH₃OH (1:1) laboratory data (Cuppen et al. 2011) for the middle and red component, respectively. In the case of the *L* bands, three laboratory data were used, pure H₂O (Fraser & van Dishoeck 2004), CO:CH₃OH (*M*-band values), and H₂O:CH₃OH (Dawes et al. 2016). The CO:CH₃OH optical depth was kept constant from the *M*-band fitting. In order to decide the best water-methanol mixing ratio (R), five variations were checked and the maximum likelihood estimation (MLE) was used to determine the best model given the higher probability. In order to achieve this goal, the OMNIFIT code was modified and the optimisation procedure adapted to allow the Monte Carlo Markov chain (MCMC) analysis. The log-likelihood function is given by

$$\ln p(\tau_\lambda^{\text{obs}} | k \cdot \tau_{\lambda, \text{true}}^{\text{lab}}) = -\frac{1}{2} \sum_n \left[\frac{(k \cdot \tau_{\lambda, \text{true}}^{\text{lab}} - \tau_\lambda^{\text{obs}})^2}{\sigma_n^2} + \ln(2\pi\sigma_n^2) \right], \quad (\text{A.2})$$

where $\tau_\lambda^{\text{obs}}$ was defined in Eq. (A.1), $\tau_{\lambda, \text{true}}^{\text{lab}}$ is the optical depth of the laboratory data, k the scale factor, and σ_n^2 is the optical depth error, propagated from the flux error. The MLE was initially found using the down-hill simplex method (Nelder & Mead 1965), and the best solution used as initial point to sample the posterior distribution using the affine-invariant MCMC package emcee (Foreman-Mackey et al. 2013). The log-likelihood comparisons are shown in Fig. A.5.

⁶ <https://hitran.org>

⁷ <https://lmfit.github.io/lmfit-py/>

Fig. A.1. *L*-band SED and optical depth of the sources towards the SVS 4 cluster. *Left*: the dotted blue and orange lines show the blackbody functions we used to determine the continuum (magenta line) by fitting the dark grey photometric points. The temperature of each blackbody component is shown in the upper left corner of each panel and is given in K. *Right*: *L*-band observations towards the SVS 4 sources on an optical depth scale. The dashed black lines are used as a reference for $\tau = 0$.

A.3. Derivation of H_2O and CH_3OH ice column density

The pure H_2O column density was calculated by integrating the optical depth of the O–H stretching mode at $3.0\ \mu\text{m}$ of the fitted laboratory spectra, after decomposing the *L*-band spectra performed by OMNIFIT, using the equation:

$$N_{\text{ice}} = \frac{1}{\mathcal{A}} \int_{\nu_1}^{\nu_2} \tau_{\nu} d\nu, \quad (\text{A.3})$$

where $\mathcal{A}$ is the band strength of a specific vibrational mode, and ν must be understood as the wavenumber in units of cm^{-1} . The band strength we used was $2 \times 10^{-16}\ \text{cm molecule}^{-1}$ taken from [Hudgins et al. \(1993\)](#).

Because we lack accurate band strengths for the $\text{H}_2\text{O}:\text{CH}_3\text{OH}$ component, mixed water and methanol column densities were derived from non-saturated and negligibly blended bands at $1660\ \text{cm}^{-1}$ ($6.0\ \mu\text{m}$) and $2827\ \text{cm}^{-1}$ ($3.57\ \mu\text{m}$),

Fig. A.2. Continued from Fig. A.1. The light grey line represents the SVS 4–9 optical depth scaled to the red wing of SVS 4–12.

respectively, following the empirical relations found by [Giuliano et al. \(2016\)](#) for a binary mixture of $\text{H}_2\text{O}:\text{CH}_3\text{OH}$:

$$N_{\text{H}_2\text{O}} = (29067 \times \tau_{1660 \text{ cm}^{-1}} - 300) \times 10^{15} \text{ molec cm}^{-2} \quad (\text{A.4})$$

$$N_{\text{CH}_3\text{OH}} = (3804 \times \tau_{2827 \text{ cm}^{-1}} + 4) \times 10^{15} \text{ molec cm}^{-2}, \quad (\text{A.5})$$

where $\tau_{1660 \text{ cm}^{-1}}$ and $\tau_{2827 \text{ cm}^{-1}}$ are the optical depth values at this position in the spectrum.

A.4. Derivation of CO ice column density

The pure CO ice column density was calculated by the equation below, taken from [Pontoppidan et al. \(2003b\)](#):

$$N_{\text{Pure CO}} = 6.03 \text{ cm}^{-1} \times \tau_{\text{peak}} \times A_{\text{bulk}}^{-1}, \quad (\text{A.6})$$

where A_{bulk}^{-1} is the band strength of the bulk ($1.1 \times 10^{-17} \text{ cm molecule}^{-1}$ – [Gerakines et al. 1995](#)), and the numerical factor takes the effect of the CDE correction into account.

Fig. A.3. *M*-band SED and optical depth of the sources towards the SVS 4 cluster. *Left*: the spline function we used to determine the continuum for the *M*-band spectra is shown in magenta. *Right*: *M*-band observations towards the SVS 4 sources on an optical depth scale. The dashed black lines are used as a reference for $\tau=0$.

The column density of CO trapped in the CO:CH₃OH sample was calculated from the oscillator number method, described in Suutarinen (2015a). A modified version of Eq. (A.3) was used,

$$N = k \cdot \frac{1}{\mathcal{A}} \int_{\nu_1}^{\nu_2} \tau_\nu d\nu, \quad (\text{A.7})$$

where k is a scale factor calculated by OMNIFIT (see Eq. A.2), and the oscillator number is the entire term given by $\frac{1}{\mathcal{A}} \int_{\nu_1}^{\nu_2} \tau_\nu d\nu$. The value used for the oscillator number of CO and CH₃OH was $5.183 \times 10^{17} \text{ cm}^{-2}$ taken from Suutarinen (2015a).

Fig. A.4. Continued from Fig. A.3.

Fig. A.5. Log-likelihood bar plot of the $\text{H}_2\text{O}:\text{CH}_3\text{OH}$ mixing ratios (R). The mixture with $R = 38\%$ provides a slightly better match of observations and models for all SVS 4 sources, except for SVS 4–3.

Appendix B: Producing gas-phase maps

B.1. Combination of interferometric and single-dish data

The combination of interferometric and single-dish data was performed using CASA version 4.6.0 and following the CASA Guide⁸ M100 Band3 Combine 4.3 (for a detailed explanation of the combination, see the CASA Guide and references therein). Initially, the APEX dataset was resampled to match the shape of the SMA datacube using the `imregrid` task in CASA. Subsequently, the two datasets were trimmed with the CASA `imsubimage` task to exclude the noisy edge regions in the single-dish data and the regions masked by the `clean` task in the interferometric data. Then the SMA non-uniform primary beam response was multiplied to the single-dish data by applying the CASA task `immath`. This step was performed to ensure that the two datasets had a common response on the sky. The SMA and APEX datasets were then combined by executing the CASA task `feather`. The `feather` algorithm applies a Fourier transform and scales the single-dish (low-resolution) data to the interferometric (high-resolution) data. Finally, it merges the two datasets with different spatial resolution, and in our case, it folds

into the SMA data the short-spacing corrections of the APEX telescope.

Figures B.2–B.4 show the integrated intensity maps of the $\text{CH}_3\text{OH } 5_0-4_0 \text{ A}^+$ line and of the CO isotopologues (^{13}CO and C^{18}O) lines using the SMA data, APEX data, and the combined SMA + APEX data. The maps distinctly illustrate that the SMA data filter out spatially extended emission associated with the cloud. On the other hand, the extended emission is very well recovered in the single-dish APEX data. Therefore it is crucial to combine interferometric and large-scale single-dish data when a quantitative analysis of the datasets is performed (e.g. derivation of column densities). The species for which most of the flux is recovered in the combination is ^{13}CO , followed by C^{18}O and CH_3OH .

B.2. CO isotopologue optical depth

When the gas ratio abundance $^{12}\text{CO}:^{13}\text{CO}:\text{C}^{18}\text{O}$ is constant, the ^{13}CO optical depth can be calculated from the line intensity ratio (Myers et al. 1983; Ladd et al. 1998), given by

$$\frac{I(^{13}\text{CO})}{I(\text{C}^{18}\text{O})} \approx \frac{1 - \exp(-\tau^{13}\text{CO})}{1 - \exp(-\tau^{13}\text{CO}/f)}, \quad (\text{B.1})$$

⁸ <https://casaguides.nrao.edu/index.php>

Fig. B.1. $I(^{13}\text{CO})/I(\text{C}^{18}\text{O})$ line intensity ratio vs. the $I(\text{C}^{18}\text{O})$ line intensity. The dashed lines indicate two optical depth regimes for ^{13}CO ; the sources are represented by coloured dots. The error bars assume a 20% error from the flux calibration.

where $I(^{13}\text{CO})$ and $I(\text{C}^{18}\text{O})$ are the line intensities of ^{13}CO and C^{18}O , respectively. $\tau^{13}\text{CO}$ is the ^{13}CO optical depth, and f is the $^{13}\text{CO}/\text{C}^{18}\text{O}$ abundance ratio. In the literature, the intrinsic ratio for the Milky Way disc is about 7–10 (Wilson & Matteucci 1992; Barnes et al. 2015). In this paper, $f=8$ is assumed. Figure B.1 shows the $I(^{13}\text{CO})/I(\text{C}^{18}\text{O})$ line intensity ratio versus the $I(\text{C}^{18}\text{O})$ line intensity, where the sources are identified by the colours. The two dashed lines indicate the line ratio

Table B.1. Integrated ^{13}CO and C^{18}O line intensities in units of $\text{Jy beam}^{-1} \text{ km s}^{-1}$ over each source position.

Source	$^{13}\text{CO} (J=2-1)$	$\text{C}^{18}\text{O} (J=2-1)$
SVS 4–2	122.80 ± 24.55	14.39 ± 2.86
SVS 4–3	105.36 ± 21.13	13.46 ± 2.73
SVS 4–4	104.00 ± 20.72	14.15 ± 2.80
SVS 4–5	122.59 ± 24.52	19.55 ± 3.91
SVS 4–6	117.22 ± 23.48	16.99 ± 3.38
SVS 4–7	127.30 ± 25.46	14.80 ± 2.96
SVS 4–8	123.97 ± 24.98	14.14 ± 2.93
SVS 4–9	119.95 ± 24.00	12.45 ± 2.50
SVS 4–10	121.57 ± 24.32	14.18 ± 2.81
SVS 4–12	116.87 ± 23.41	17.73 ± 3.51

associated with the $\tau^{13}\text{CO}$. In the trivial case that the ^{13}CO emission is optically thick and the C^{18}O emission is optically thin, C^{18}O increases compared to ^{13}CO along the LoS. Consequently, the ratio between the two lines will decrease, as shown in Fig. B.1. Although the $\tau^{13}\text{CO}$ does indicate the ^{13}CO emission is only moderately optically thick, the decreasing profile indicates that the C^{18}O emission is optically thin and is therefore more reliable to calculate the ^{12}CO column density assuming local thermodynamic equilibrium (LTE) conditions. This result is still valid when an $^{13}\text{CO}/\text{C}^{18}\text{O}$ abundance ratio (f) equal to 7 or 10 is assumed.

Table B.2. Integrated CH_3OH line intensities in units of $\text{Jy beam}^{-1} \text{ km s}^{-1}$ over each source position.

SVS	5_0-4_0 E^+	5_1-4_1 E^-	5_0-4_0 A^+	5_1-4_1 E^+	5_2-4_2 E^-
SVS 4–2	0.66 ± 0.13	6.23 ± 1.24	7.98 ± 1.60	0.50 ± 0.10	0.19 ± 0.10
SVS 4–3	...	0.69 ± 0.14	0.97 ± 0.20	...	...
SVS 4–4	...	1.73 ± 0.35	1.10 ± 0.22	...	...
SVS 4–5	0.63 ± 0.13	3.82 ± 0.76	1.65 ± 0.50	0.41 ± 0.13	0.12 ± 0.05
SVS 4–6	0.50 ± 0.10	3.37 ± 0.67	3.89 ± 0.78	0.85 ± 0.17	0.92 ± 0.19
SVS 4–7	0.16 ± 0.05	2.74 ± 0.60	1.26 ± 0.45	0.43 ± 0.10	0.33 ± 0.07
SVS 4–8	...	1.32 ± 0.26	1.32 ± 0.26	...	...
SVS 4–9	0.30 ± 0.07	1.48 ± 0.30	1.97 ± 0.40	0.12 ± 0.04	...
SVS 4–10	0.32 ± 0.07	1.12 ± 0.22	2.42 ± 0.48	...	...
SVS 4–12	0.11 ± 0.04	4.29 ± 0.86	4.55 ± 0.91	0.19 ± 0.05	0.25 ± 0.07

Notes. Not provided numbers mean that the integrated intensities are below 5σ of the noise level.

Fig. B.2. *Left:* $\text{CH}_3\text{OH } 5_0 - 4_0 \text{ A}^+$ line emission observed by the SMA. *Middle:* $\text{CH}_3\text{OH } 5_0 - 4_0 \text{ A}^+$ line emission detected by the APEX telescope. *Right:* $\text{CH}_3\text{OH } 5_0 - 4_0 \text{ A}^+$ line emission resulting from the SMA + APEX combination. All lines are integrated between 5 and 13 km s^{-1} . Contours are at 3σ , 6σ , 9σ , etc. The synthesised beam is shown in white in the bottom left corner of each panel. The dark red crosses and the white star illustrate the positions of the SVS 4 stars and of SMM 4, respectively.

Fig. B.3. *Left:* $^{13}\text{CO } 2-1$ line emission observed by the SMA. *Middle:* $^{13}\text{CO } 2-1$ line emission detected by the APEX telescope integrated between 0 and 15 km s^{-1} . *Right:* $^{13}\text{CO } 2-1$ line emission resulting from the SMA + APEX combination. All lines are integrated between 0 and 13 km s^{-1} . Contours are at 3σ , 6σ , 9σ , etc. The synthesised beam is shown in white in the bottom left corner of each panel. The dark red crosses and the white star illustrate the positions of the SVS 4 stars and of SMM 4, respectively.

Fig. B.4. *Left:* $\text{C}^{18}\text{O } 2-1$ line emission observed by the SMA. *Middle:* $\text{C}^{18}\text{O } 2-1$ line emission detected by the APEX telescope. *Right:* $\text{C}^{18}\text{O } 2-1$ line emission resulting from the SMA + APEX combination. All the lines are integrated between 4 and 11 km s^{-1} . Contours are at 3σ , 6σ , 9σ , etc. The synthesised beam is shown in white in the bottom left corner of each panel. The dark red crosses and the white star illustrate the position of the SVS 4 stars and of SMM 4, respectively.

Appendix C: Producing an H₂ column density map

The production of the H₂ column density map is accomplished by making use of the submillimeter continuum (SCUBA-2) maps at 850 μm (Herczeg et al. 2017). The equations and the conversion factors used here come from Kauffmann et al. (2008) and are briefly explained below.

The H₂ column density N_{H_2} is related to the observed flux per beam S_{ν}^{beam} , the dust opacity k_{ν} , and the Planck function $B_{\nu}(T)$ by

$$N_{\text{H}_2} = \frac{S_{\nu}^{\text{beam}}}{\Omega_{\text{A}} \mu_{\text{H}_2} m_{\text{H}} k_{\nu} B_{\nu}(T)}, \quad (\text{C.1})$$

where Ω_{A} is the beam solid angle, μ_{H_2} is the molecular weight per hydrogen molecule, and m_{H} is the hydrogen atom mass. When rearranged in useful units, Eq. (C.1) yields

$$N_{\text{H}_2} = 2.02 \times 10^{20} \text{ cm}^{-2} (e^{1.439 (\lambda/\text{mm})^{-1} (T/10 \text{ K})^{-1}} - 1) \left(\frac{k_{\nu}}{0.01 \text{ cm}^2 \text{ g}^{-1}} \right) \left(\frac{S_{\nu}^{\text{beam}}}{\text{mJy beam}^{-1}} \right)^{-1} \left(\frac{\theta_{\text{HPBW}}}{10 \text{ arcsec}} \right)^{-2} \left(\frac{\lambda}{\text{mm}} \right)^{-3}, \quad (\text{C.2})$$

where the dust opacity k_{ν} is $0.0182 \text{ cm}^2 \text{ g}^{-1}$, the telescope beam θ_{HPBW} is 15 arcsec, and the wavelength of the observations λ is 850 μm .

The dust opacity adopted in the calculation of the H₂ column density comes from Ossenkopf & Henning (1994), where an H-density of 10^6 cm^{-3} and dust with thin ice-mantles coagulating

Fig. C.1. H₂ column density map of SVS 4, calculated from the SCUBA-2 dust emission map at 850 μm from Herczeg et al. (2017), assuming $T_{\text{dust}} = 15 \text{ K}$. The crosses indicate the position of the SVS 4 stars and of SMM 4.

for 10^5 yr were assumed. The adopted dust temperatures are 10, 15, and 20 K. The dust opacities and dust temperature comply with the standard assumptions made by the c2d collaboration. The dust emission is provided by ground-based sub-millimeter observations at 850 μm from the SCUBA-2 camera at the *James Clerk Maxwell Telescope* as part of the proposal ID M16AL001 (Herczeg et al. 2017).