Onsala Proposal

Carl 0115.F-9306

Gaseous and Icy Methanol in Star-Forming Regions - resubmitted

Semester: feb2025 **Science Cat.: ISM and star formation**

Abstract

Complex organic molecules (COMs) are detected in all stages of star-formation, from cold, dark clouds to hot cores and corinos. Methanol is the simplest COM and considered a very important key molecule in the formation of more complex species. It does not form efficiently in the gas-phase at low temperatures, but laboratory studies have shown that it is produced from hydrogenation of CO ices at low temperatures. Ice mantles are thermally desorbed into the gas-phase when the grains are heated enough in the vicinity of a forming protostar, but observations of gas-phase methanol in cold environments indicate that other desorption mechanisms like photo-desorption, cosmic ray-induced desorption or reactive desorption can be effective as well. We propose to complete our previous study of methanol observations of a sample of thirteen embedded low and high-mass protostars by observing the remaining 7 sources at 193 GHz.

Applicants

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Is this a long term proposal: No

No overall scheduling requirements

Observing runs

run	telescope	instrument	time request (minimal)	frequency (GHz)	weather (pwv)	LST range	comments/constraints
A	APEX	SEPIA180 (159-211 GHz)	6h (4h)	193	> 2 mm	12-23	205 in the USB

Targets

Source	RA	Dec	Epoch	Vlsr (km/s)	Duration (min)	Runs	Comments
IRAS 17081-2721	17:11:17.28	-27:25:08.1	J2000	4.0	36	A	low-mass
CrA IRS 7B	19:01:56.41	-36:57:28.0	J2000	6.0	36	A	low-mass
SSTGC 726327E	17:46:53.31	-28:32:01.2	J2000	32.0	36	A	high-mass
W 33A	18:14:39.44	-17:52:01.3	J2000	36.0	36	A	high-mass
SVS 20	18:29:57.75	+01:14:05.9	J2000	7.0	36	A	low-mass
GL 7009S	18:34:20.91	-05:59:42.2	J2000	41.0	36	A	high-mass
R CrA IRS 5	19:01:48.03	-36:57:21.6	J2000	6.0	36	A	low-mass

Scientific Rationale

The presence of interstellar ices on the surface of dust grains has been confirmed quite some time ago by infrared observations towards young stellar objects (YSOs, e.g. Willner et al., 1982; Whittet et al., 1996). Theory predicts that ice mantles start to form at high densities and low temperatures during the prestellar core phase of star-formation (e.g. Taquet, Ceccarelli, and Kahane, 2012; Jin and Garrod, 2020). The ice mantles are mainly composed of water ice (H_2O) with smaller amounts of other simple molecules like carbon monoxide (CO), ammonia (NH_3), or methane (CH_4), but also more complex species like methanol (CH_3OH). It has been suggested that many of the complex organic molecules (COMs) with six and more atoms can be formed at the surface of dust grains (e.g. Charnley, Rodgers, and Ehrenfreund, 2001). When the temperature rises during the protostellar core phase, the trapped ice species are slowly released into the gas phase as soon as their sublimation temperature is exceeded. The gas phase abundances of complex molecules around low-mass and high-mass protostars are studied by e.g. Blake et al. (1987), Cazaux et al. (2003), and Bottinelli et al. (2004). However, we can also observe the release of significant amounts of ice species in regions lacking sufficient heating (e.g. Bacmann et al., 2012; Vastel et al., 2014; Jiménez-Serra et al., 2016; Taquet et al., 2017), indicating that other desorption mechanisms like photo-desorption, cosmic ray-induced desorption or the release of chemical energy upon formation (reactive desorption, e.g. Chuang et al., 2018) can be effective.

There are a number of studies that seek to better constrain the relation between ice and gas phase abundances for species like H_2O, CO, and CH_3OH in order to better understand the role and efficiency of different desorption mechanisms. As far as we know, this has been done for a total of 21 low-mass YSOs (Öberg et al., 2009; Öberg, Lauck, and Graninger, 2014; Perotti et al., 2020; Perotti et al., 2021) and four high-mass YSOs (Fayolle et al., 2015). In particular, methanol is the simplest of the complex organic molecules and considered a very important key molecule in the formation of even more complex species. It does not form efficiently in the gas-phase at low temperatures, but laboratory studies have shown that it is produced in abundance from hydrogenation of CO ices at low temperatures (Fuchs et al., 2009). In the case of the studied low-mass sources, the methanol gas-to-ice ratios differ significantly from 10^{-4} to 4×10^{-3}, depending on the source. However, the ratios have been derived without taking into account spatial temperature variations within a given source. Since methanol is released into the gas-phase from both thermal and non-thermal processes, it can be expected to exist in the gas-phase at different kinetic temperatures, both in the warmer core regions around the protostars as well as in the colder envelopes. In the case of the high-mass sources, this effect has been taken into account and Fayolle et al. (2015) report higher values of gas phase methanol towards the warmer central region. Observations have suggested that for low-mass YSOs embedded in envelopes with significant ice abundances the column densities of warm ($\sim$25 K) and cold ($<$10 K) gas-phase methanol are similar (Öberg, Lauck, and Graninger, 2014). At the same time, laboratory studies show that methanol mixed in with water ice in grain mantles would mainly co-desorb with water at temperatures significantly above 100 K (Collings et al., 2004). We aim to further explore methanol desorption fraction variation with temperature in both low and high mass star formation.

We propose to observe a sample of embedded protostars, eight low-mass and five high-mass, for which methanol ice abundances are reported in the literature (Gürtler et al., 2002; Pontoppidan et al., 2003; Boogert et al., 2008; An et al., 2017). An overview of the sample set is given in Tab. 2. Except the high-mass source W 33A, the selected sources are not considered in any of the previous studies on gas-ice relations (Öberg et al., 2009; Öberg, Lauck, and Graninger, 2014; Fayolle et al., 2015; Perotti et al., 2020; Perotti et al., 2021).

Facilities Requested

Considering how methanol excitation is very sensitive to the local temperature, by observing multiple transitions spanning a wide range of excitation temperatures it is possible to identify and quantify the column densities for different temperature components without spatially resolving them. For this, APEX suits really well as it provides a wide frequency coverage at high spectral resolution, with access to the southern star-forming regions. We propose to observe a set of methanol emission lines with upper state energies in the range 16–130 K, see Table 1, covered by two spectral setups, one using the SEPIA receiver (192.0 GHz LSB) and the other using nFLASH (236.1 GHz USB). We choose the nFLASH setup to ensure simultaneous observations of ^{13}CO and C^{18}O in the LSB, which will provide a separate estimate of the total gas column density at the current resolution. The spectral setups will also simultaneously cover, among other, a set of formaldehyde lines, formic acid lines and CH_3CN lines - the last providing an additional temperature estimate if detected.

Observing Requirements and Observing Plan

Based on the measured CH_3OH ice column densities provided in Table 2, and assuming a lower gas-to-ice ratio of 1×10^{-4} (Öberg et al., 2009; Perotti et al., 2021), we expect lower limits to the gas-phase methanol column densities of $0.04 - 3.54 \times 10^{14}\,\mathrm{cm}^{-2}$ depending on the source. With gas-to-ice ratios instead in the upper part of the range as noted by Perotti et al. (2021), 4×10^{-3}, the lowest gas-phase methanol column density would instead be $1.6 \times 10^{14}\,\mathrm{cm}^{-2}$.
For all sources, see Table 2, we first plan to conduct single pointings in both frequency setups, see Table 1. As a guideline in the time estimate, we wish to securely (at the 3σ level) detect the strongest methanol A-type transitions (193.4 GHz and 241.8 GHz) for a methanol column density of $0.4 \times 10^{14}\,\mathrm{cm}^{-2}$ (assuming a temperature of 20 K, so some of the E-type lines will be of similar strength as the strongest A-type lines). This will require an antenna temperature noise level of about 30 mK which, according to the APEX online calculator for nFLASH230, is achieved after 27 min of observing time (at 0.1 km/s resolution). In the case of SEPIA180 we arrive at 36 min per source when the pwv is 2.0 mm. For the 13 sources, 14 hrs of observing time is needed. In the case of the two low CH_3OH ice column sources (IRAS17081 and GL 989) we ask for an additional 3 hrs.
For most of the sources, it is essential that a suitable reference position is confirmed to be free of emission before starting the above mentioned observations. We estimate this will take 10-15 mins per source or about 2.5 hr in total (this will be performed with the nFLASH230 setup which also covers CO lines). The CrA sources can share the same reference position. Including 2 hr overhead (for tuning, pointing and focussing, receiver change) we ask for 21.5 hr of nFLASH230 time and 9.5 hrs of SEPIA180 time.

Suggested 2025 Observations

In this proposal we only ask for time to complete project `0110-9314` which was observed in 2022 and 2023. Some examples of our previous observations can be seen in Figs 1 and 2. Seven sources have not yet been observed at 193 GHz. These observations are only single pointings each requiring about 36 mins (see above). Thus we ask for a **total time of 6.5 hrs** (including time for pointing, focus, calibration, and tuning).

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Figures and Tables

Table 1: Lines covered in the SEPIA180 setup.

Molecule	Transition	Frequency, GHz	Comment
SEPIA 192.0 GHz LSB setup			
c-HCOOH	$6_{1,6} - 5_{0,5}$	192.955	
CH_3OH	4-3	193.4-193.5	several
CH_3CN	11-10	202.3	several low K
CH_3OH	$1_{1,1} - 2_{0,2}$	205.791	weak

Table 2: Source sample for 2025. If not stated otherwise, the water and methanol ice column densities are taken from Boogert et al. (2008).

Source	Type	RA [hh:mm:ss.ss]	Dec [dd:mm:ss.s]	v_{LSR} [$\mathrm{km\,s^{-1}}$]	$N_{ice}(H_2O)$ [$10^{18}\,\mathrm{cm^{-2}}$]	$N_{ice}(CH_3OH)$ [$10^{18}\,\mathrm{cm^{-2}}$]
SVS 20	low-mass	18:29:57.75	+01:14:05.9	7	1.69 ± 0.16	0.11 ± 0.02
IRAS 17081	low-mass	17:11:17.28	−27:25:08.2	4	1.31 ± 0.13	0.04 ± 0.01
CrA IRS 7B	low-mass	19:01:56.41	−36:57:28.0	6	11.01 ± 1.97	0.75 ± 0.13
GL 7009S	high-mass	18:34:20.91	−05:59:42.2	41	11.31 ± 2.26	3.54 ± 0.53
GL 2136	high-mass	18:22:26.32	−13:30:08.2	26	4.57 ± 0.45	0.39 ± 0.09
W 33A	high-mass	18:14:39.44	−17:52:01.3	36	12.57 ± 3.14	1.85 ± 0.09
S726327E	high-mass	17:46:53.31	−28:32:01.2	32	2.80 ± 0.50[c]	0.47 ± 0.05 [a]

[a] An et al. (2017).

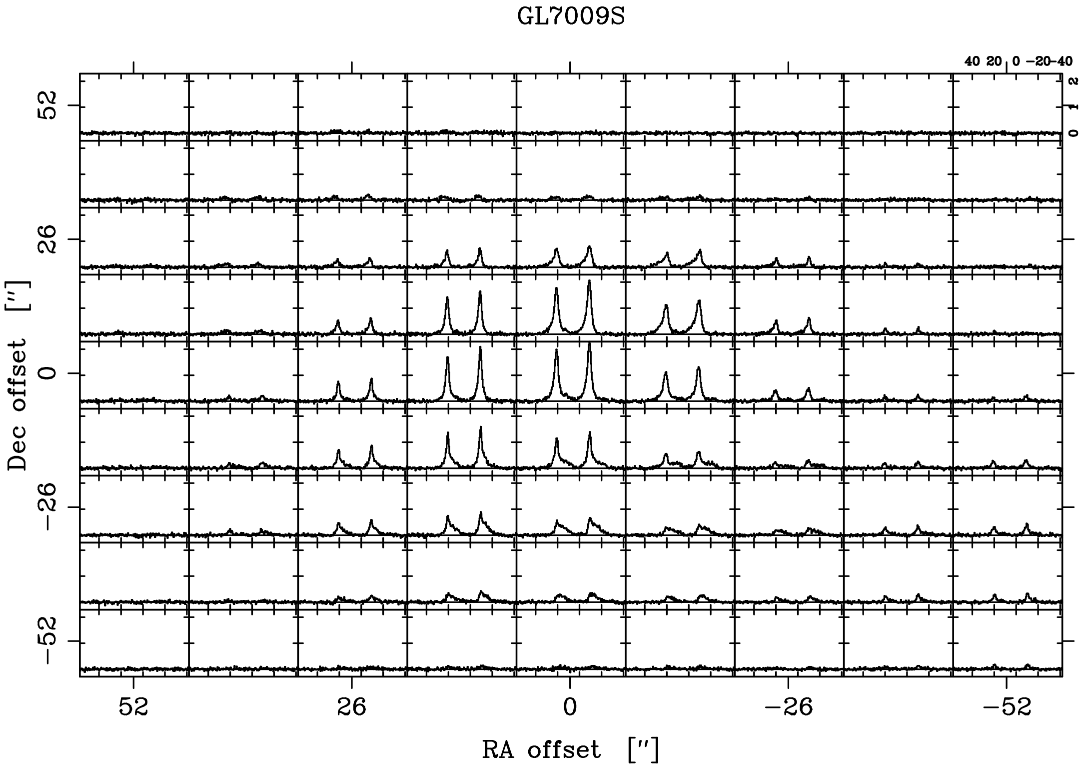

Figure 1: Methanol 241 GHz map spectra towards the embedded high-mass protostar source GL7009S observed with APEX for project `0110-9314a`.

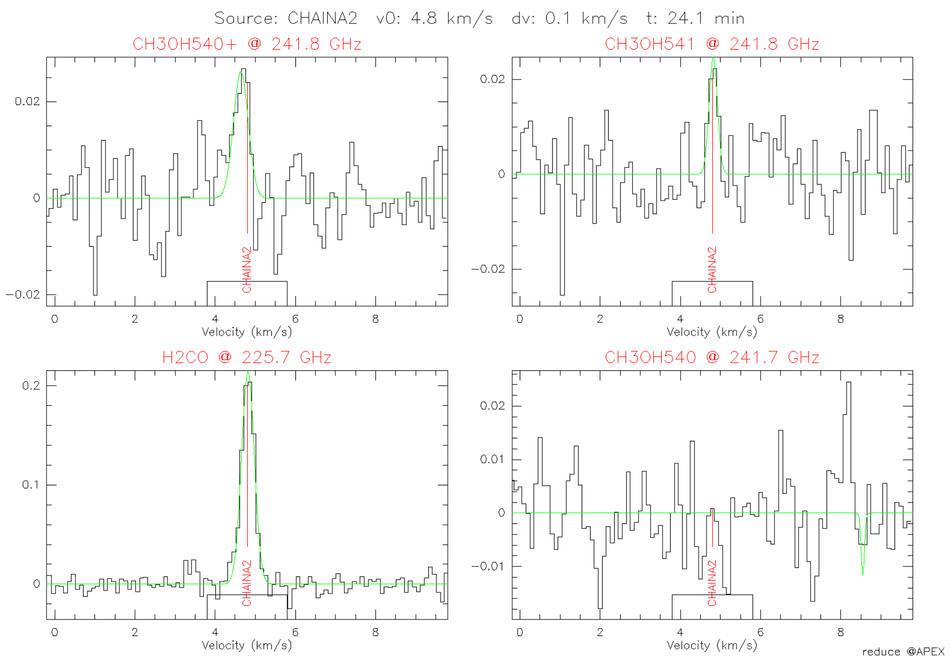

Figure 2: Methanol and formaldehyde spectra towards the low-mass region Cha I observed with APEX for project `0110-9314a` in 2023.

Students involved

Student	Level	Applicant	Supervisor	Applicant	Expected completion date	Data required
Tadeus Carl	Doctor	Yes	Dr. Eva Wirström	Yes	2026/10	No

Linked proposal submitted to this TAC: No

Linked proposal submitted to other TACs: No

Relevant previous Allocations: No

Additional remarks

TBD

Observing run info :