*SF2A 2022*
*J. Richard, A. Siebert, E. Lagadec, N. Lagarde, O. Venot, J. Malzac, J.-B. Marquette, M. N'Diaye, D. Briot (eds)*

# ICE AND GAS OBSERVATIONS AND MODELS IN THE DENSE CORE L429C

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**Abstract.** Star formation is a long process with one of the first stages, called cold core, characterized by medium density (a few $10^4$ to $10^5$ cm$^{-3}$), low temperature (15 K and below), and low to no UV. In these dense environments, a rich chemistry happens at the surface of dust grains. Species from the gas-phase can stick at the surface of the grains and further react to form complex organic molecules, such as methanol. Understanding these processes is essential to trace the origin of some molecules in space that cannot be formed by reactions in the gas-phase only. The desorption mechanisms of these species from the grains are not fully understood yet. Under such extreme conditions, thermal desorption is not possible as not enough energy is available. Several non-thermal desorption mechanisms are studied in laboratory astrophysics (experiments or theoretical calculations) to give quantitative constraints that are then included in astrochemical models. With the arrival of a new generation of satellites and telescopes, it becomes easier and easier to unveil the mystery of the molecules desorption as the abundances are now easier to obtain. Observing the cold core L429C, with NOEMA and the IRAM 30m single dish telescope, we were able to constrain the gas-phase abundance of key species, such as CO and $CH_3OH$, and compare it with the methanol ice abundances observed with *Spitzer* in the same region. Comparing the gas and ice abundances at the same positions allows us to put observational constraints on the non-thermal desorption mechanisms of methanol as this molecule cannot be formed in the gas-phase. Comparing these results with the predictions of our chemical model nautilus, we try to understand which non- thermal desorption mechanism dominates under these conditions if any.

Keywords: ice, star formation, desorption mechanisms, gas

## 1 Introduction

Star formation has been studied for years and recent observations allowed us to get a better understanding of the full picture (Jørgensen et al. 2020). Cold cores are formed under the action of turbulence, magnetic field and gravity, leading to high density region ($n_{H_2} > 10^4$ cm$^{-2}$) with very low temperature (T $\sim$ 10 K). Such environment results in a rich chemistry that takes place at the dust grain surface. As the surfaces act as catalysis, species like methanol are predominantly formed on dust grains but commonly observed in the gas-phase in cold cores (Dartois et al. 1999; Dartois 2005; Pontoppidan et al. 2004). It is formed by successive hydrogenations of CO (formed in the gas-phase and depleted on the grain surface). At such a low temperature, the presence of methanol in the gas-phase is a clear indicator that non-thermal desorption from the grain surface is at play where thermal desorption cannot happen (Garrod et al. 2007; Ioppolo et al. 2011). The non-thermal desorption processes considered are chemical desorption (Dulieu et al. 2013; Minissale et al. 2016; Wakelam et al. 2017), photodesorption with UV photolysis (Öberg et al. 2007; Bertin et al. 2016; Cruz-Diaz et al. 2016), grain sputtering induced by cosmic-ray impacts (Dartois et al. 2018, 2019, 2020). These mechanisms are partly destructive, releasing both intact methanol and fragments, that participate in the subsequent chemistry. The efficiency of such mechanisms is not well known and is being investigated in laboratory experiment.

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L429C is a cold (T < 18 K) and dense ($n_H \sim 10^{22}$ $cm^{-3}$) core located in the Aquila Rift (Stutz et al. 2009). The core presents an advanced chemistry: it has a high CO depletion with a high deuteration factor (Bacmann et al. 2002) and it is one of the rare core where methanol ices have been observed (Boogert et al. 2011) with *Spitzer*.

The goal of this work is to obtain gas abundances of key molecules observed with NOEMA and IRAM 30m, to compare it with the ice column densities derived by *Spitzer* and to constrain the non-thermal desorption mechanisms releasing methanol in the gas-phase at low temperature.

## 2 Observations and Results

### 2.1 Observations

The gas observations were made with NOEMA and 30m IRAM telescope during 2020. We observed between 94.5 and 117.8 GHz and 168 - 169.8 GHz, frequency bands with IRAM 30m, with a spatial resolution of 0.2 km $s^{-1}$. We obtain 360 x 360 arcsec maps with a spatial resolution of 7 arcsec. The data reduction was done using GILDAS and more precisely, MAPPING and CLASS packages. We managed to detect 19 lines corresponding to 11 molecules with a peak intensity larger than 3 times the local rms: $CH_3OH$, OCS, CCS, $HC_3N$, CS, SO, CO, $^{13}CO$, $C^{17}O$, $C^{18}O$, CN, $H_2S$. The NOEMA data cube did not show any signal at any frequency. This indicates that there is a spatial filtering with no molecular emission smaller than approximately 30". Merging the two sets of data was therefore adding noise to the 30m maps. We decided to use the single dish observations only.

### 2.2 Abundance maps

We derived abundance maps from the gas-phase observations using a radiative transfer inversion code. To do so, we developed Python tools to derive physical parameters. Temperature is taken from *Herschel* database. Starting with dv, the line width, we used ROHSA developed by Marchal et al. (2019). It allowed us to fit multiple Gaussian on each spectra per pixel to obtain an equivalent FWHM. The resulting "cleaned" Gaussian are used as a denoised intensity map that we use in the next steps.

Next, we constrain $n_{H2}$ using Bron et al. (2018) method. It estimated the volume density from the column density for simple source by taking multiple assumptions: the density is smoothly increasing from outer to inter region of the cloud and it assumes isotropy with no privileged direction for the spatial density. It then estimated the typical lengthscale $l$ of the cloud using $N_H$ threshold masks. Finally, to obtain the $n_H$ density, it divides $N_H$ by $l$.

Next, we use RADEX (van der Tak et al. 2007), a one-dimensional non-LTE radiative transfer code. We input the multiple parameters obtained earlier (line frequency, $T_{kin}$, $n_{H2}$, dv and N). We obtain as an output a theoretical integrated intensity ($T_{ex}$ and lines opacity).

Finally, we make a 3 sigma cut to select high signal to noise ratio. The best column density corresponds to the one with the minimum $\chi_2$. The abundance map is then obtained by dividing each pixel by the corresponding $H_2$ density (see Fig.1).

Our main results on the abundances maps are all molecules abundances are decreasing with the visual extinction and density, whereas $CH_3OH$ abundance stays flat. Consequently, depletion is observed at higher densities for all molecules except methanol.

### 2.3 Chemical Modelling

We used the chemical model Nautilus (Ruaud et al. 2016) to reproduce L429C observed abundances and tried to understand which non-thermal desorption mechanism is the most efficient. Nautilus simulates the chemical evolution in the gas, on the grain surface and within the ice mantle (3 phases). It is based on kinetic rates and surface data from lab experiments and theoretical calculations. We input physical parameters (mean gas temperatures and mean visual extinction Av in function of density). The output are the abundances of gas and ice as a function of time. We use the distance of disagreement $d$ defined by Wakelam et al. (2021) to quantify the agreement between models and observations. As a result, Av and density follow the same trend: lower times reproduce higher densities and higher time reproduce lower densities. At higher densities, molecules stick to the grains faster and depletion is more efficient.

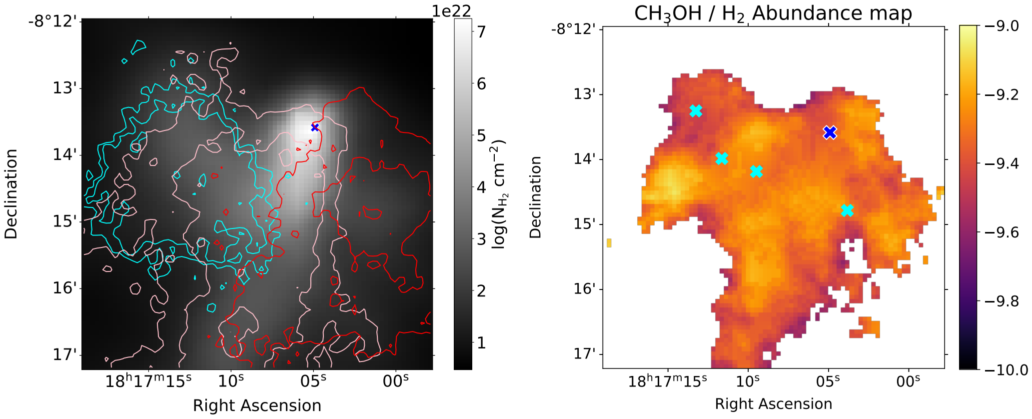

**Fig. 1.** *Left*: $C^{18}O$ integrated intensity contours over plotted on the $N_{H_2}$ *Herschel* map (grey color). Cyan contours: 5.95 - 6.25 km.s$^{-1}$, pink contours: 6.25 - 7 km.s$^{-1}$, red contours: 7 - 7.6 km.s$^{-1}$. *Right*: Observed gas-phase abundances maps with respect to $H_2$. The cyan crosses on methanol map correspond to the positions of the methanol ice observations reported by Boogert et al. (2011). The dark blue cross is the dust peak

### 2.4 Budget of gas and ice methanol

Combining our gas-phase abundance of methanol and the ice observations of Boogert et al. (2011), we can compare the total budget of $CH_3OH$ (gas and ice) with our model predictions. We observe that both in observations and in the models, the reservoir of methanol is found in the ices. Our model reproduces the observed ice column density of methanol with less than a factor 2. Non-thermal desorption in our model is mostly produced by grain sputtering induced by cosmic rays. Our observed discrepancy could be due to the fact that while desorbing, the methanol does not fragment in our simulations (Dartois et al. 2019). At low density, we may have a more efficient destruction of methanol due to larger cosmic-ray ionization rates or a less efficient recombination to the methanol fragments to form back the molecule. We found that the observation predicts that less than 0.093% of methanol is desorbed from the ices. Our models predict an efficiency between less than 0.0075%.

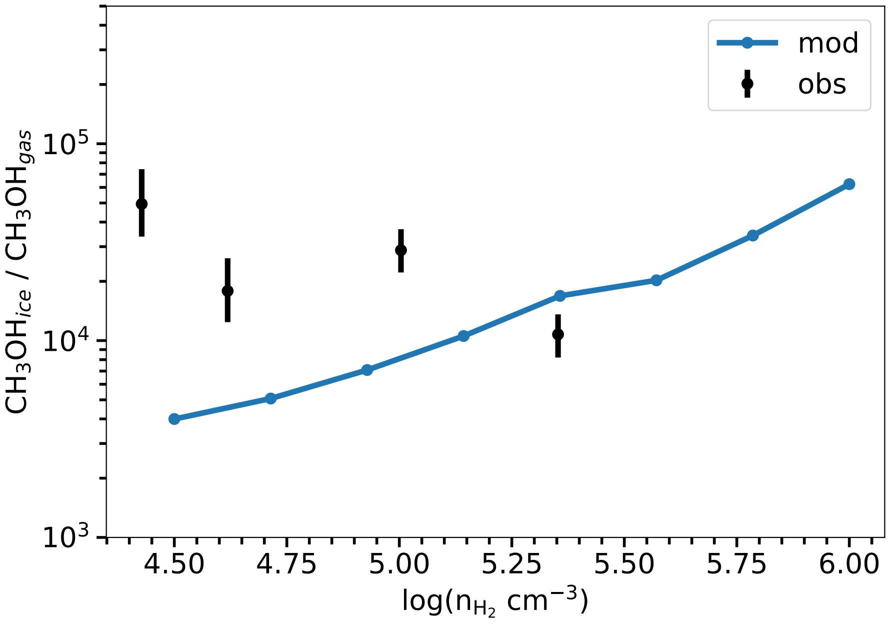

**Fig. 2.** Gas to ice abundance ratios of methanol as a function of density obtained by the model (solid lines) for the best times and the four observation points (black dots)

## 3 Conclusions

We conducted observations of the cold core L429-C with IRAM 30m telescopes. We detected 11 molecules including methanol and isotopologues of CO. We summarize below our main findings:

- We studied the dynamic of the cloud and showed that there were multiple components (up to three) in the spectra.
- We built a method to obtain the gas abundances in the core, constraining the column density with temperature, density, line width and interpolating these 3 parameters with theoretical integrated intensity from RADEX. After a 3 $\sigma$ cut, we computed the column density with a $\chi^2$ test. We divided the obtained column density with the $n_{H_2}$ density to derive abundances.
- The dust peak is characterised by a depletion in most of our observed sample in the gas phase, except for methanol which has a fairly flat abundance along the density range.
- Using Nautilus, we ran multiple grid of models covering the observed physical parameters to model the abundance of the observed molecules through time and found the best model by using the distance of disagreement. We showed that higher densities are reproduced with a smaller time, whereas lower densities regions seem to have formed already a long time ago.
- We found that the observation predicts less than 0.093% of methanol is desorbed from the ices. Our models predict an efficiency less than 0.0075%. Both in the model and in the observations, the methanol reservoir is found to be in the ice form.

AT, VW, PG, JN, ED, MC acknowledge the CNRS program ”Physique et Chimie du Milieu Interstellaire” (PCMI) co-funded by the Centre National dEtudes Spatiales (CNES). We would like to thank the 30m IRAM team and NOEMA team for the observations (proposals 111-21 and 079-20) and the data treatment.

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