Onsala Proposal

Punanova 0115.F-9308

Highly deuterated starless cores with low CO freeze out: a chemical puzzle - continuation

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

Abstract

The deuterium fraction is known to increase inside the CO depletion zone in dense prestellar cores. Recent observations have revealed the presence of dense cores with high deuterium fractions and low CO-depletion factors which contradicts chemical models of dense cores. One way to reconcile theory with observations is to have small or clumpy cores. With ALMA ACA, we observed the N2D+(3-2), N2H+(3-2) and C18O(2-1) transitions towards eight of these cores in Ophiuchus. Four of them showed an unexpectedly extended emission, and we need total power observations to reveal full flux and analyze the data correctly. We also found the C18O emission to be ubiquitous with no sign of the depletion zones. We propose to do otf maps towards the four cores to complement the existing ACA observations. With that, we will measure the deuterium fraction and the CO depletion factor, on 5" scales. We also will be able to observe the most rare 13O17C isotopologue and reveal the mystery of the abundant CO in the highly deuterated dense cores.

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	SEPIA345 (277-371 GHz)	40h (40h)	279.51	any		N2H+(3-2)

Targets

Source	RA	Dec	Epoch	Vlsr (km/s)	Duration (min)	Runs	Comments
Oph-B1-MM1	16:27:08.70	-24:27:50.0	J2000	3.97	606	A	
Oph-C-W	16:26:50.00	-24:32:49.0	J2000	3.55	606	A	
Oph-B1B2-MM1	16:27:11.30	-24:27:39.0	J2000	4.0	606	A	
Oph-E-MM4	16:27:10.60	-24:39:30.0	J2000	4.2	606	A	

Scientific rationale

Deuterated molecules are preferentially formed in the cold ($\simeq$10 K) and dense (n(H_2)>10^4 cm^{-3}) cloud cores that are the precursors to star formation. This is mainly due to the fact that the deuteron-proton exchange reaction H_3^++HD$\rightleftharpoons$$H_2D^+$+$H_2$ is exothermic by about 200 K (Millar et al., 1989) and, if the gas temperature is below 30 K, it only proceeds from left to right. H_2D^+ can then cede a deuteron to abundant species such as CO and N_2, producing DCO^+ and N_2D^+. Deuterium fractionation is particularly efficient in cold dense gas where CO and other neutrals, which could destroy H_3^+ and its deuterated isotopologues, are frozen onto dust grains (e.g. Dalgarno & Lepp, 1984; Caselli et al., 1999).

Crapsi et al. (2005) derived an empirical relation between deuterium fraction (R_D) and CO-depletion factor (f_d) in starless cores, with the deuterium fraction increasing with increasing CO-depletion factor. This positive correlation is a natural result of chemical evolution in cold dark clouds, consistent with theoretical predictions (e.g. Caselli et al., 2008; Kong et al., 2015; Harju et al., 2017), and confirmed with observations of a large sample (>100) of cores in the Taurus, Ophiuchus, and Perseus molecular clouds (e.g., Caselli et al., 2002, 2008; Emprechtinger et al., 2009). However, the observations of dense cores in Perseus (Friesen et al., 2013) and Ophiuchus (Punanova et al., 2016) revealed a total of 11 abnormal starless cores with high deuteration ($R_D \geq 0.20$) and low CO freeze-out ($f_d < 5$), in contradiction with the Crapsi et al. (2005) relationship and theoretical predictions.

One possible explanation for these abnormal cores is variable beam filling factors. N_2H^+ and N_2D^+ are higher density gas tracers than CO, such that they should have smaller spatial extents. The CO, on the other hand, is widespread, so the CO depletion was measured on the scale of the beam (22$''$). This hypothesis predicts that the N_2D^+ emission should only be present on small spatial scales ($< 22''$) and that there should be a small CO depletion zone within these cores with size scale comparable to the N_2D^+ emission (see the sketch in the left panel of Fig. 1).

Previous observations

We performed ALMA ACA observations to reveal the zones of the compact N_2D^+ emission and CO depletion (project 2018.1.01639.S). We observed eight highly deuterated ($R_D \geq 0.2$) starless cores in L1688, Ophiuchus, which show very low CO depletion factors ($f_d < 5$, see the right panel of Fig. 1 and Table 1). From the parameter space exploration of Caselli et al. (2008) and Kong et al. (2015), large values of R_D (> 0.10) cannot be achieved in standard conditions without significant CO freeze-out ($f_d > 5$). Following the empirical correlation of Crapsi et al. (2005), we expected to see 2–15 times higher depletion towards the 4$''$–10$''$-size CO depletion zones of these cores (see the last column in Table 1) and reconcile theory with observations. However, the ACA data analysis revealed substantial flux loss in all three program lines (N_2H^+ and N_2D^+ (3–2) and $C^{18}O$(2–1), see Fig. 3) that must come from extended emission, from the area much larger then the expected depletion zones. Besides, the $C^{18}O$(2–1) emission was ubiquitous and suggested either high optical depth of the lines or a high gas-phase CO abundance. To analyse the data correctly and reveal full flux, we need total power observations.

Previous APEX observations. In the APEX project 0113.F-9311, 10.9 h of the proposed 50.8 h were observed in April and August 2024. The total power observations of N_2D^+(3–2) and $C^{18}O$(2–1) were completed, the obtained intensities of N_2D^+(3–2) are given in Table 1, the rms of $\simeq$50 mK (T_a) needed to combine the total power and the interferometric data was reached, as proposed. The (2–1) line of the most rare CO isotopologue, $^{13}C^{17}O$ is detected towards Oph-C-W and Oph-E-MM4 with $T_{mb} \simeq 100$ mK that proves high CO abundance towards the cores.

Objectives

With the APEX maps combined with the ACA data we will recover the total molecular lines flux and perform the correct data analysis. We will constrain the distribution of the dense gas (with N_2D^+), measure deuterium fraction (with N_2H^+ and N_2D^+). With these data, coupled with gas-grain chemical codes including deuterium and spin chemistry (e.g. Sipilä et al., 2015), we will be able to measure the electron fraction (with methods similar to those described in Caselli et al., 1998), a crucial parameter for the dynamical evolution of magnetized dense cloud cores. We will be finally able either to reveal the compact depletion zones or will show the fact of the very pequliar environment, where CO remain abundant in gas which does not disturb high deuteration. This would require a substantial revision of our understanding of the basic chemical processes regulating the deuterium fractionation, taking also into account possible dust evolution, as suggested by Christie et al. (2012).

Our targets. Table 1 and Fig. 2 show the starless cores in L1688 which have high deuterium fractions (≥ 0.2 taking the uncertainties into account), low CO depletion factors (≤ 1) and lie away from the Crapsi et al. (2005) correlation (right panel of Fig. 1). All of the cores in our sample are isolated from other cores, young stellar objects (see the latest YSOs catalogue by Dunham et al., 2015) and outflows (see White et al., 2015), and have no compact embedded sources (Kirk et al., 2017) such that they should not be influenced by stellar feedback.

Facilities requiested

We request the APEX radio telescope and the SEPIA345 spectrometer for this project. Our project requires reaching high sensitivity at the 280 GHz band with high spectral resolution to be able to combine the data with the ALMA ACA data set which can be done only via deep integration with the APEX antenna and the SEPIA345 spectrometer.

Observing Requirements

We propose to do on-the-fly maps towards four sources with two spectral setups. To be able to combine the on-the-fly maps with the ACA data, we need to cover the area twice as big as the ACA primary beam (35.7″x2=71.4″ at 279 GHz), have the same spectral resolution (0.079 km/s) and reach the same sensitivity, wich is 44 mK (T_{mb}) for N_2H^+(3–2), that is 34 mK in T_a, taking into account the efficiency of the antenna.

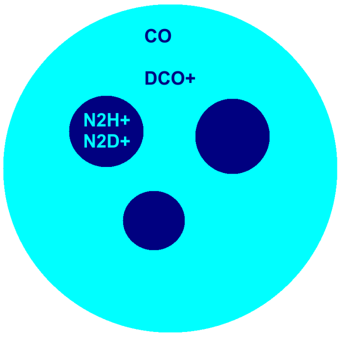
We have used the OTF observing time calculator at APEX V10.0 to estimate the total time needed to achieve our goal. For the calculation we assume a dumptime of 1 seconds and a sampling corresponding to 1/3 of the beam. We plan to do the OTF of 72 x 72 arcsec using SEPIA345 tuned to 279.51 GHz in the LSB, selecting a spectral resolution of 0.0792 km/s and assuming a typical source elevation of 45 deg and a typical PWV of 1.0 mm for 279 GHz, we could get down to a noise of 34 mK[Ta*] in 10.1 hours for one map of N_2H^+(3–2)(including telescope and calibration overheads). For four sources that gives 40.4 hours in total.

Observing Plan

We propose to do the on-the-fly maps matching the requirements for the total power observations towards four cores listed in Table 1, in the remaining N_2H^+ (3–2) line, to combine it with the ACA data.

Scheduling Requirements

There are no special requirements for the schedule.



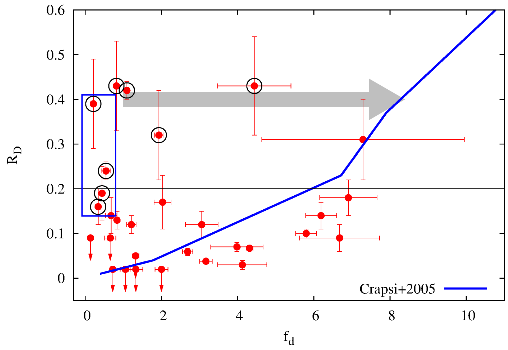


Figure 1: **Left:** Simplified interpretation of the expected result – small depletion zones where CO is highly frozen out (dark blue) are diluted with a large beam size and observed as one large core (cyan). **Right:** Deuterium fraction as a function of CO depletion factor in the L1688 cores (Punanova et al., 2016). The cores proposed for otf mapping are inside the blue rectangle. The black open circles show the sample of the ACA project. The black line marks a deuterium fraction of $R_D \geq 0.20$. The blue line shows the empirical correlation found by Crapsi et al. (2005). The grey horizontal arrow shows that a group of cores in the top left part of the plot should move to the right if high CO depletion zones are found at the centres of these cores with ALMA.

Table 1: The starless cores with $R_D \geq 0.2$ and $f_d < 5$ (from Punanova et al., 2016) and their expected parameters.

Core	$T_{mb}^{N_2H^+(a)}$ (K)	$T_{mb}^{N_2D^+(b)}$ (K)	$T_{mb}^{N_2D^+(c)}$ (K)	R_D	f_d	$f_d^{(d)}$	$L^{(e)}$ (au)	$l^{(f)}$ ($''$)
B1-MM1	0.7	0.6	0.50	0.39 ± 0.10	0.22 ± 0.07	8.0	500–1070	3.7–7.8
B1B2-MM1	1.4	0.6	0.67	0.24 ± 0.02	0.55 ± 0.12	6.8	860–1150	6.3–8.4
C-We	0.5	0.4	0.17	0.16 ± 0.04	0.34 ± 0.07	4.9	790–1360	5.8–9.9
E-MM4	0.6	0.3	0.33	0.19 ± 0.06	0.44 ± 0.07	5.7	840–1260	6.1–9.2

Notes. [a]expected peak intensity in N_2H^+(3–2); [b]expected peak intensity in N_2D^+(3–2); [c]peak intensity in N_2D^+(3–2) according to the APEX observations from the project 0113.F-9311; [d]expected CO depletion factor; [e]expected size of the depletion zones in au; [f]expected size of the depletion zones in arcsec.

References

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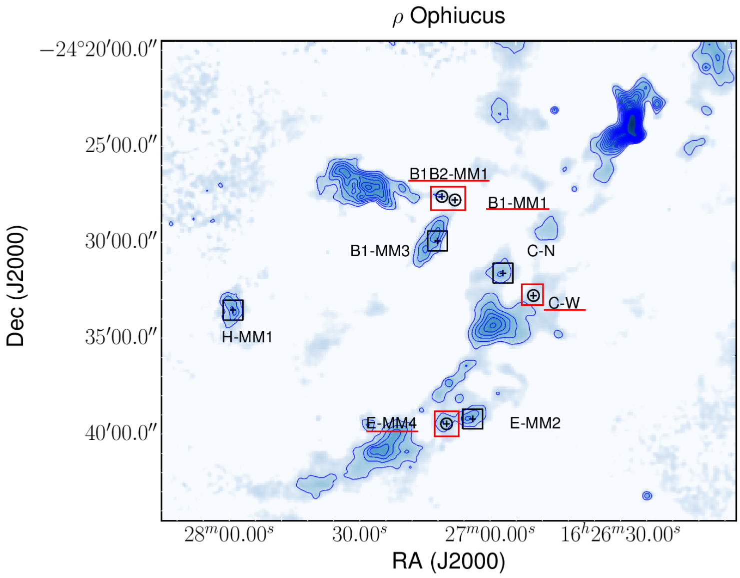

Figure 2: 850 μm dust continuum emission of L1688 mapped by the Submillimeter Common-User Bolometer Array (SCUBA, Di Francesco et al., 2008); the beam size is 22.9″. Contour levels go from 0.2 Jy beam^{-1} in steps of 0.2 Jy beam^{-1} (3 σ). The cores proposed for otf mapping are marked with red rectangles and underline. The black crosses show the sample of the ACA project.

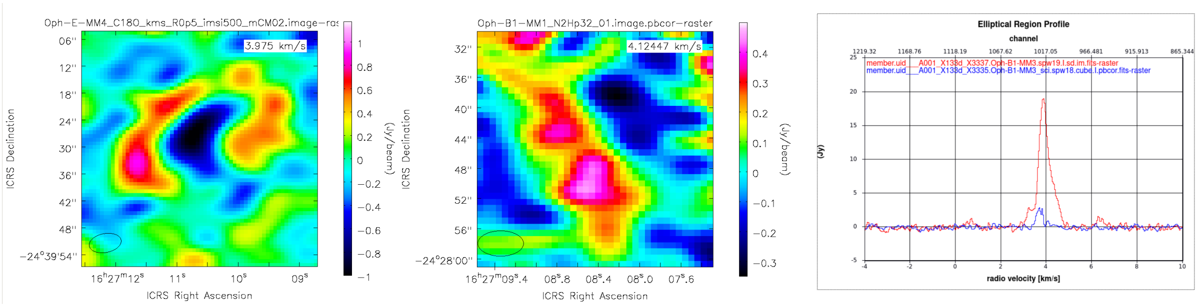

Figure 3: Evidences of missing flux: negative flux in the images of $C^{18}O$(2–1) (left) and N_2H^+(3–2) (center) after deep cleaning; and the comparison of the total power and ACA-only flux density in N_2D^+ towards the core where the total power observations were provided (right).

No PhD Students involved

Linked proposal submitted to this TAC: No

Linked proposal submitted to other TACs: No

Relevant previous Allocations: Yes

Project 0113.F-9311, 10.9 of 50.8 h were observed. Run A (nFLASH230) was fully observed, run B (SEPIA345) was not observed.

No additional remarks

Observing run info :