Publication Year	2015
Acceptance in OA@INAF	2020-04-06T08:17:13Z
Title	CO depletion in ATLASGAL-selected high-mass clumps
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DOI	10.1051/eas/1575025
Handle	http://hdl.handle.net/20.500.12386/23861
Series	EAS PUBLICATIONS SERIES
Number	75-76

Conditions and Impact of Star Formation
R. Simon, R. Schaaf and J. Stutzki (eds)
EAS Publications Series, ***75-76*** *(2015) 147–151*

CO DEPLETION IN ATLASGAL-SELECTED HIGH-MASS CLUMPS

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Abstract. In the low-mass regime, it is found that the gas-phase abundances of C-bearing molecules in cold starless cores rapidly decrease with increasing density. Here the molecules tend to stick to the grains, forming ice mantles. We study CO depletion in the TOP100 sample of the ATLASGAL survey, and investigate its correlation with evolutionary stage and with the physical parameters of the sources. We use low-J emission lines of CO isotopologues and the dust continuum emission to infer the depletion factor f_D. RATRAN one-dimensional models were also used to determine f_D and to investigate the presence of depletion above a density threshold. The isotopic ratios and optical depth were derived with a Bayesian approach. We find a significant number of clumps with a large CO depletion, up to ~20. Larger values are found for colder clumps, thus for earlier evolutionary phases. For massive clumps in the earliest stages of evolution we estimate the radius of the region where CO depletion is important to be a few tenths of a pc. CO depletion in high-mass clumps seems to behave as in the low-mass regime, with less evolved clumps showing larger values for the depletion than their more evolved counterparts, and increasing for denser sources.

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DOI: 10.1051/eas/1575025

1 Introduction

In the low-mass regime, molecules such as CO and CS tend to freeze onto the dust grains in the densest and coldest part of starless cores (*e.g.* Bergin, Tafalla 2007; Caselli 2011). This is observed as an abundance drop for these molecules (referred to as depletion) in the central parts of the core, identified by means of dust continuum emission (*e.g.* Tafalla, *et al.* 2002, and references therein). CO depletion is a temperature- and density-sensitive process; at low temperatures and high densities the depletion is higher, because under those conditions it is easier for the molecules to attach themselves to the grains. When protostars are formed in the core, the temperature increases, and at $T \sim 20$–$25\,\mathrm{K}$ the molecules evaporate from grains back into the gas phase. Depletion can thus vary substantially during the process of star formation, and can be used as an evolutionary indicator.

Discordant evidence for depletion exists for high-mass objects, with both claims of significant CO freeze-out onto grains (*e.g.*, Fontani *et al.* 2012) and of canonical abundances (*e.g.*, Zinchenko *et al.* 2009). In Giannetti *et al.* (2014) we investigated the CO abundance in a large sample of massive clumps, selected from ATLASGAL, by means of its rarer isotopologues. The clumps have been selected to be in different evolutionary phases, so that we can also study changes in CO abundance in massive clumps during their evolution.

2 The TOP100 sample

The ATLASGAL survey constitutes an excellent tool for selecting massive clumps. The TOP100 sample includes the brightest submm sources of the survey, in four different classes, depending on the IR properties of the source (from most evolved to least evolved): **IRB)** The brightest sources of the whole survey, excluding the Central Molecular Zone. These clumps are also detected at $8\,\mu$m and $24\,\mu$m; **RMS)** Sources classified as a Massive Young Stellar Object (MYSO) in the Red MSX Sources survey (Urquhart *et al.* 2008); **D8)** Objects dark at $8\,\mu$m; **D24)** Sources dark at $24\,\mu$m. Above, "brightest" refers to the submm peak flux at $870\,\mu$m. Sources are classified as $24\,\mu$m or $8\,\mu$m dark if their average $24\,\mu$m or $8\,\mu$m flux density within the ATLASGAL beam is smaller than the average flux at the same wavelength in their vicinity. All the sources in this sample have an unambiguous distance (Giannetti *et al.* 2015; König *et al.* 2015, submitted); the evolution of the physical properties of the sources are investigated in König *et al.* (2015), submitted, showing also that this sample is representative of massive clumps in different stages of evolution.

3 CO depletion

All sources were observed with APEX/FLASH in $C^{17}O$(3–2); sources in the North were observed with the 30-m telescope in the (1–0) transition of $C^{18}O$, ^{13}CO, $C^{17}O$, $^{13}C^{18}O$, and sources in the South with APEX1 in ^{13}CO and $C^{18}O$ (2–1). The column densities of CO are derived assuming LTE, and correcting for the optical

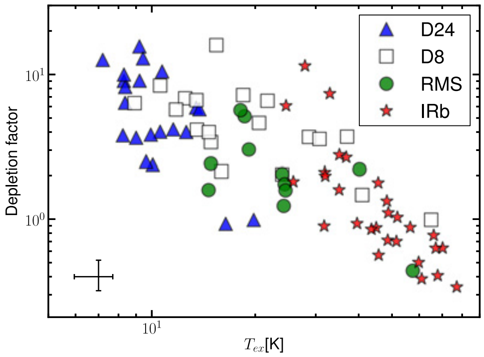

Fig. 1. CO depletion factors from $^{12}C^{17}O$ as a function of T_{ex}. A typical uncertainty is shown in the bottom left corner.

depth, whereas the column density of molecular hydrogen $N(H_2)$ was calculated from the ATLASGAL peak flux (Schuller *et al.* 2009), assuming that gas and dust are coupled.

Figure 1 shows the CO depletion factor as a function of the excitation temperature. Here, the depletion factor, which is defined as the ratio of the expected and observed abundance, is determined taking into account the CO abundance gradient with the Galactocentric distance. Cold and dense objects are more prone to high-levels of depletion, because its timescale decreases with increasing density, while for higher temperatures, molecules evaporate more rapidly. CO depletion factor and the L/M ratio are also weakly anti-correlated.

The previous analysis assumes that molecules are in LTE. In order to have more solid results for CO abundances we used RATRAN (Hogerheijde & van der Tak 2000) to build one-dimensional models of the clumps for typical parameters of the objects and for a subsample of individual sources (*cf.* Fig. 2), confirming the previous trends.

In recent works the ammonia (1,1), (2,2) and (3,3) inversion transitions were observed towards a subsample of sources in the TOP100 sample (Wienen *et al.* 2012; Wienen *et al.* 2015) and the dust temperature was determined for all of them (König *et al.* 2015, submitted). The temperatures derived in these ways are typically higher than those calculated from CO for sources in groups D8 and D24, especially for the latter, with typical values ~20 K. To reproduce the observed line intensities with RATRAN, assuming a temperature of 20 K, we used a drop profile for the CO abundance, i.e. the abundance is canonical when the density is below a given value, while all CO is locked onto grains for densities above this value, again for typical parameters of the sources and for a subsample (*cf.* Fig. 3).

In conclusion, we find that depletion is important for cold, massive clumps in general, with f_D up to 20 for the less evolved sources, with typical sizes of the region affected by depletion of the order of a few tenths of a pc, and densities above which CO is depleted comparable to those observed in the low mass regime

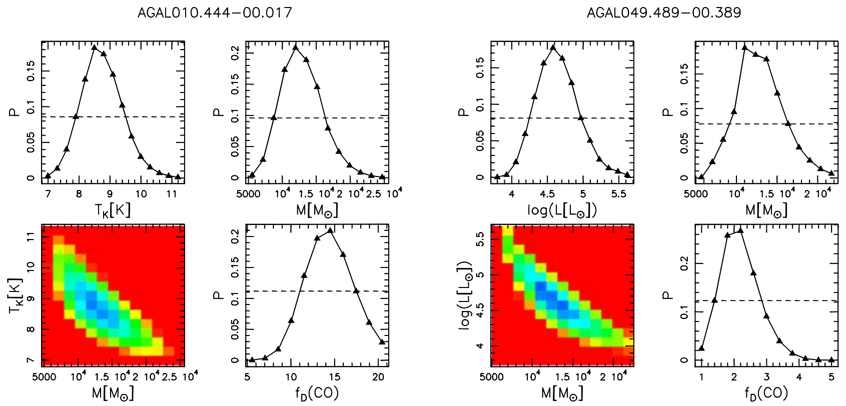

Fig. 2. Examples of the RATRAN results for individual sources, using models with a constant abundance profile; the left source belongs to D24, the right one to IRB. For each source the panels show: *(bottom left)* joint probability distribution of mass and T or L (depending on whether the model is centrally heated or isothermal), marginal probability distribution of temperature/luminosity *(top left)*, of mass *(top right)*, and of depletion factor *(bottom right)*.

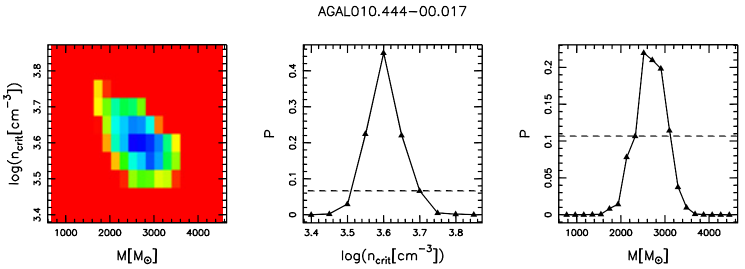

Fig. 3. Example of the RATRAN results for an individual source, using a model with a drop profile. The panels show: *(left)* joint probability distribution of mass and critical density of molecular hydrogen above which all CO is locked onto dust grains, marginal probability distribution of the critical density above which CO is depleted *(centre)*, and mass *(right)*.

(few $\times\, 10^4$ cm^{-3}). The presence of depletion may in part explain why masses much larger than the virial mass are found, especially among the less evolved sources: if the CO emission comes mainly from the low-density outer layers, the molecules may be subthermally excited, leading to an overestimate of the dust masses.

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