Abstract

 Studying the physical and chemical properties of cold and dense molecular clouds is crucial for the understanding of how stars form. Under the typical conditions of infrared dark clouds, CO is removed from the gas phase and trapped onto the surface of dust grains by the so-called depletion process. This suggests that the CO-depletion factor ($f_D$) can be a useful chemical indicator for identifying cold and dense regions (i.e., prestellar cores). We have used the 1.3 mm continuum and $^{13}$CO (2–1) data observed at the resolution of $\sim$5000 au in the ALMA Survey of 70 $\mu$m Dark High-mass Clumps in Early Stages (ASHES) to construct averaged maps of $f_D$ in 12 clumps to characterize the earliest stages of the high-mass star formation process. The average $f_D$ determined for 277 of the 294 ASHES cores follows an unexpected increase from the prestellar to the protostellar stage. If we exclude the temperature effect due to the slight variations in the NH$_3$ kinetic temperature among different cores, we explain this result as a dependence primarily on the average gas density, which increases in cores where protostellar conditions prevail. This shows that $f_D$ determined in high-mass star-forming regions at the core scale is insufficient to distinguish among prestellar and protostellar conditions for the individual cores and should be complemented by information provided by additional tracers. However, we confirm that the clump-averaged $f_D$ values correlate with the luminosity-to-mass ratio of each source, which is known to trace the evolution of the star formation process.

Unified Astronomy Thesaurus concepts: Infrared dark clouds (787); Star forming regions (1565); Star formation (1569); Massive stars (732); Interstellar medium (847); Astrochemistry (75); Interstellar line emission (844)

Supporting material: machine-readable table

1. Introduction

Although high-mass stars ($M > 8$–10 $M_\odot$) represent a small fraction compared to less massive counterparts, they play a major role in shaping the physical and chemical properties of the interstellar medium (ISM). The formation of H II regions at the end of the high-mass star formation process may favor conditions for triggering a secondary star formation cycle (Elmegreen 1998), involving molecular gas that is richer in complex organic molecules (COMs; Herbst & van Dishoeck 2009), a large number discovered in the hot molecular cores around massive young stellar objects (mYSOs; e.g., Kurtz et al. 2000; Cesaroni 2005). There is also evidence that the Sun was formed in a cluster that originally hosted high-mass stars (e.g., Adams 2010). Therefore, studying the details of the formation process of high-mass stars is crucial to understand how the chemical composition of the ISM evolves and how life arises from the organic materials produced during the star formation process.

In the past few decades, several theoretical scenarios have been proposed to describe the high-mass star formation process (e.g., Bonnell et al. 2001; McKee & Tan 2002; Tигe et al. 2017; Kumar et al. 2020; Padoan et al. 2020). These scenarios differ in the initial physical assumptions and predict different formation timescales. The identification and systematic study of the early stages of the high-mass star formation process, before the formation of mYSO (s), is hence crucial for distinguishing between the many existing scenarios (e.g., Zhang et al. 2009; Zhang & Wang 2011; Wang et al. 2014; Sanhueza et al. 2017, 2019).

Infrared dark clouds (IRDCs), originally identified in absorption against the galactic background in the mid-IR at...
8 μm (e.g., Perault et al. 1996; Egan et al. 1998), are so far considered the most likely birthplaces of high-mass stars. These are ubiquitous and extended (>10 pc) filamentary structures throughout the Galactic disk, which fragment into clumps and cores, with typical sizes of ~1 pc and <0.1 pc, respectively (e.g., Carey et al. 1998; Rathborne et al. 2006; Simon et al. 2006a, 2006b; Battersby et al. 2010; Peretto et al. 2016; Pokhrel et al. 2018; Li et al. 2022; Chevance et al. 2022). By combining the IR and radio continuum properties obtained from several galactic plane surveys (e.g., MSX, Price et al. 2001; MIPSGAL, Carey et al. 2009; ms, Urquhart et al. 2009; ATLASGAL, Schuller et al. 2009; Hi-GAL, Molinari et al. 2010; CORNISH, Hoare et al. 2012),16 clumps can be classified into evolutionary stages.

As originally reported by Saraceno et al. (1996) for the low-mass regime, the high-mass clumps belonging to different phases also lie in different regions of the $L$-$M$ diagram (see Molinari et al. 2008), which compares the circumstellar envelope mass ($M$) and the bolometric luminosity ($L$) for a given clump. The luminosity-to-mass ratio ($L/M$) of the clumps increases from the prestellar to the more evolved H II stage as a signature of forming YSOs and has therefore been used as an additional diagnostic tool to identify clumps at different evolutionary stages (e.g., Molinari et al. 2008; Elia et al. 2017; Giannetti et al. 2017b; Urquhart et al. 2018, 2022; Sabatini et al. 2021). According to this general scheme, clumps that lack 24 and 70 μm emission also show a lower $L/M$ ratio and are usually associated with the quiescent/prestellar stage (e.g., Zhang et al. 2014; Chambers et al. 2009; Sanhueza et al. 2012, 2013, 2019; Guzmán et al. 2015). However, even under these conditions, it is not possible to completely rule out the presence of star-forming activity in these clumps, which can reveal the presence of cores at different evolutionary stages when observed at high resolution (e.g., Feng et al. 2016b; Li et al. 2019, 2020; Sanhueza et al. 2019; Morii et al. 2021; Tafoya et al. 2021; Sakai et al. 2022).

Additional chemical constraints have been proposed over time to better characterize the evolutionary picture of the high-mass star formation process. Under the typical physical conditions of dense regions in IRDCs, $n(H_2) > 10^4$ cm$^{-3}$ and $T_{\text{gas}} < 20$ K, a well-known example of chemical constraint is given by the estimates of the CO depletion (e.g., Kramer et al. 1999; Bergin et al. 2002; Caselli et al. 2008; Wiles et al. 2016; Sabatini et al. 2019; Feng et al. 2020), which has been used in particular to identify the youngest clumps (e.g., Fontani et al. 2006; Pillai et al. 2007; Giannetti et al. 2014).

How much of CO is depleting onto the surface of dust grains is usually characterized by the depletion factor (e.g., Caselli et al. 1999; Fontani et al. 2012; Sabatini et al. 2019), defined as the ratio between the expected CO/H$_2$ abundance ($X_{\text{E}}^{\text{CO}}$) and the observed one ($X_{\text{O}}^{\text{CO}}$):

$$f_D = \frac{X_{\text{E}}^{\text{CO}}}{X_{\text{O}}^{\text{CO}}} = \frac{X_{\text{E}}^{\text{CO}} N(H_2)}{N(CO)},$$

where $N(H_2)$ and $N(CO)$ are the H$_2$ and CO column density, respectively. CO-depletion factors of up to a few tens have been derived on clump scales in various samples of young, high-mass star-forming regions (e.g., Thomas & Fuller 2008; Fontani et al. 2012; Feng et al. 2016a, 2020). The estimation of $f_D$ could be a suitable and convenient way to identify the cold/prestellar gas also at core scales. However, very few and isolated estimates of $f_D$ on these scales are found in the literature in high-mass star-forming regions, with extreme values of $f_D$ up to 100–1000 (Zhang et al. 2009; Morii et al. 2021; Rodríguez et al. 2021). In the absence of additional evidence for the high-mass regime, in this study we aim to test whether the CO-depletion factor can be considered a reliable tracer for cores at different evolutionary stages, embedded in high-mass star-forming regions.

This work is structured as follows: In Section 2 we describe the sample and the data set on which this study is based. In Section 3 we report on the derivation of the maps of $N(H_2)$ and C$^{18}$O used to construct the final $f_D$ maps. In Section 4 we discuss the variation in the averaged $f_D$ obtained for a population of cores at different evolutionary stages. Finally, in Section 5 we summarize our conclusions.

### 2. Sample and Data Reduction

The ALMA Survey of $70 \mu m$ Dark High-mass Clumps in Early Stages (ASHES; Sanhueza et al. 2019) provides an ideal basis for detailed studies of the earliest stages of the high-mass star formation process. In a pilot study (Sanhueza et al. 2019), 12 massive $70 \mu m$ dark clumps were mosaicked with ALMA in the dust continuum at $\sim224$ GHz ($\sim1''/2$ resolution) and used to characterize clump fragmentation (Table 1). We refer to Sanhueza et al. (2019) for a detailed description of the source selection criteria. From the dust continuum, a total of 294 cores were detected (excluding those located at the edges of the observed fields—i.e., $\sim20\%$–$30\%$ power point—where flux estimates are more uncertain).18 ASHES was designed to map the molecular emission of a large number of molecules in the ALMA Band-6, including CO, C$^{18}$O, H$_2$CO, CH$_3$OH, SiO, $^{32}$CS, $^{13}$CS, N$_2$D$^+$, DCN, DCO$^+$, and CCD. These tracers are used to characterize cores from a chemical point of view, allowing their classification into different evolutionary stages (see Li et al. 2020; Morii et al. 2021; Tafoya et al. 2021; Sakai et al. 2022; S. Li et al. 2022, in preparation).

Of the total population of 294 cores, $\sim71\%$ of cores (210 cores) are classified as prestellar, lacking any star formation signatures, while $\sim29\%$ (84 cores) are classified as protostellar candidates, being associated with molecular outflows and/or “warm core” line emission (i.e., H$_2$CO and CH$_3$OH lines with high upper energy levels).  

Since different chemical conditions were assumed for the identification of the protostellar cores, they were additionally divided into three categories (Sanhueza et al. 2019; Li et al. 2020): (1) Cores with molecular outflows (i.e., 24 cores, corresponding to $\sim8\%$ of the total population) identified via CO, SiO, and/or H$_2$CO lines and in which no “warm cores” lines were detected. (2) “Warm cores” (34 cores, $\sim12\%$) representing an evolutionary phase prior to the hot molecular core phase typically found to be associated with high-mass protostars. This class lacks in molecular

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16 ATLASGAL: the Atacama Pathfinder EXperiment (APEX, Güsten et al. 2006) Telescope Large Area Survey of the Galaxy; CORNISH: the Coordinated Radio and Infrared Survey for High-Mass Star Formation; Hi-GAL: Herschel (Pilbratt et al. 2010) InfraRed Galactic Plane Survey; MIPSGAL: Multiband Imaging Photometer (MIPS; Rieke et al. 2004) Galactic Plane Survey; MSX: Midcourse Space Experiment Survey of the Galactic Plane; ms: the Red MSX Source Survey.

17 The Atacama Large Millimeter/submillimeter Array (ALMA; Wooten & Thompson 2009).

18 The complete catalog is available at https://cdsarc.cds.unistra.fr/viz-bin/cat?J/ApJ/886/102.
### Table 1

Summary of the Physical and Chemical Properties of the ASHES Sources

| Clump-ID | d_{c} | R_{dc} | Mass | R_{eff} | \( \text{rms} \) (mJy beam\(^{-1}\)) | \( \nu_{\text{max}}^{(C^{18}O)} \) (km s\(^{-1}\)) | \( \sigma_{\nu_{\text{max}}}^{(C^{18}O)} \) (km s\(^{-1}\)) | \( \gamma \) | \( X_{\text{mol}}^{(C^{18}O)} \) | \( f_{D} \) |
|----------|-------|--------|------|---------|----------------|----------------|----------------|-----|----------------|------|
| G010.991-00.082 | 3.7 | 4.91 | 2230 | 27 | 0.115 | 5.150 ± 0.3 | 0.7 ± 0.3 | 74 | 5.5 × 10^{-7} | 2.8 |
| G014.492-00.139 | 3.9 | 4.79 | 5200 | 23 | 0.168 | 5.200 | 41.2 ± 0.2 | 0.8 ± 0.2 | 72 | 5.7 × 10^{-7} | 4.6 |
| G028.273-00.167 | 5.1 | 4.73 | 1520 | 24 | 0.164 | 5.310 | 80.2 ± 0.2 | 0.8 ± 0.2 | 71 | 5.9 × 10^{-7} | 3.5 |
| G327.116-00.294 | 3.9 | 5.63 | 580 | 20 | 0.089 | 4.150 | -58.8 ± 0.2 | 0.7 ± 0.2 | 85 | 4.3 × 10^{-7} | 1.9 |
| G331.372-00.116 | 5.4 | 4.56 | 1640 | 24 | 0.083 | 4.270 | -87.8 ± 0.1 | 0.6 ± 0.1 | 69 | 6.3 × 10^{-7} | 1.6 |
| G332.969-00.029 | 4.4 | 5.03 | 730 | 28 | 0.080 | 4.320 | -66.5 ± 0.2 | 0.7 ± 0.2 | 75 | 5.3 × 10^{-7} | 1.2 |
| G337.541-00.082 | 4.0 | 4.08 | 1180 | 22 | 0.068 | 3.220 | -54.6 ± 0.1 | 0.6 ± 0.1 | 76 | 5.2 × 10^{-7} | 2.1 |
| G404.179-00.242 | 4.1 | 4.87 | 1470 | 37 | 0.094 | 5.190 | -51.9 ± 0.2 | 0.8 ± 0.2 | 73 | 5.6 × 10^{-7} | 1.1 |
| G404.222-00.167 | 4.0 | 4.96 | 760 | 19 | 0.112 | 5.490 | -51.7 ± 0.1 | 0.7 ± 0.1 | 74 | 5.4 × 10^{-7} | 1.2 |
| G404.232-00.146 | 3.9 | 4.98 | 710 | 25 | 0.139 | 5.440 | -50.5 ± 0.1 | 0.8 ± 0.1 | 75 | 5.3 × 10^{-7} | 1.7 |
| G431.039-00.114 | 3.6 | 5.23 | 1070 | 27 | 0.070 | 3.340 | -43.4 ± 0.1 | 0.7 ± 0.1 | 79 | 4.9 × 10^{-7} | 1.1 |
| G434.489-00.416 | 2.9 | 5.75 | 810 | 29 | 0.068 | 3.480 | -28.6 ± 0.1 | 0.5 ± 0.1 | 87 | 4.1 × 10^{-7} | 1.9 |

Notes.

- Taken from Whitaker et al. (2017).
- Derived from the Millimetre Astronomy Legacy Team 90 GHz (MALT90) Survey (Contreras et al. 2017).
- The clump’s effective radius was derived in Sanhueza et al. (2019) from Gaussian fitting to the ATLASGAL dust continuum emission at 870 μm.
- The rms of dust continuum emission at 1.3 mm are taken from Sanhueza et al. (2019), while those of C^{18}O are computed from the data cubes presented in Section 2.
- Median local standard of rest velocities (\( \nu_{\text{max}}^{(C^{18}O)} \)) and the velocity dispersions (\( \sigma_{\nu_{\text{max}}}^{(C^{18}O)} \)) obtained from the C^{18}O (2–1) employing the Python Spectroscopic Toolkit (PySpecKit; Ginsburg & Mirocha 2011; Ginsburg et al. 2022; see also Appendix A).
- Gas-to-dust ratio derived using Equation (3) (see Section 3.1).
- Expected C^{18}O/H_{2} abundance derived using Equation (6) (see Section 3.3).
- Average \( f_{D} \) of each clump determined following the procedure discussed in Section 4.

### 3. Analysis and Results

#### 3.1. \( \text{H}_{2} \) Column Density Maps

The beam-averaged \( \text{H}_{2} \) column density is computed in each pixel from the primary beam (PB) corrected ALMA continuum flux density at 1.3 mm, \( F_{1.3 \text{ mm}} \), as (e.g., Schuller et al. 2009)

\[
N(\text{H}_{2}) = \frac{F_{1.3 \text{ mm}} \gamma}{B_{1.3 \text{ mm}}(T_{\text{dust}}) \Omega_{\text{app}} \kappa_{1.3 \text{ mm}} \mu_{\text{H}} b_{H}}
\]

where \( B_{1.3 \text{ mm}}(T_{\text{dust}}) \) is the Planck function at 1.3 mm with a dust temperature \( T_{\text{dust}} \); \( \Omega_{\text{app}} \) is the beam solid angle,\(^{19} \mu_{\text{H}} = 2.8 \) is the \( \text{H}_{2} \) mean molecular weight (Kauffmann et al. 2008; see their Section A.1), and \( b_{H} \) is the mass of the hydrogen atom. We adopt a value of \( \kappa_{1.3 \text{ mm}} = 0.9 \) cm\(^{2}\) g\(^{-1}\), which corresponds to the opacity of thin icy mantle dust grains at gas densities of 10\(^5\) cm\(^{-3}\) (Ossenkopf & Henning 1994).

In Equation (2) we assume \( T_{\text{dust}} \) equal to the \( \text{NH}_{3} \) kinetic temperature, \( T_{\text{kin}}^{\text{NH}_{3}} \), derived from \( \text{NH}_{3} \) (1, 1) and (2, 2) transition lines obtained as part of the CACHMC survey (the Complete ATCA\(^{20} \) Census of High-Mass Clumps; D. Allingham et al. 2022, in preparation) at \( \sim 5'' \) angular resolution. Under typical

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\(^{19}\) This is calculated assuming an equivalent radius for a circular beam with the same area as the ALMA beam.

\(^{20}\) The Australia Telescope Compact Array (ATCA; e.g., Wilson et al. 2011).
conditions prevailing in IRDCs, the gas–dust thermal coupling is effective in regions where the gas density exceeds $10^{4.5} \, \text{cm}^{-3}$ (e.g., Goldsmith 2001). Overall, this density threshold is fulfilled in the entire population of cores identified in ASHES (e.g., Sanhueza et al. 2019; see also the additional discussion in Section 3.3). The methodology to derive the temperature from the NH$_3$ observations is based on Mangum & Shirley (2015) and will be presented in a forthcoming paper describing the survey (D. Allingham et al. 2022, in preparation; see also Friesen et al. 2009; Hogge et al. 2018; Keown et al. 2019). The temperature maps are finally regridded to the same pixel size as the ALMA maps. We mask the native temperature maps where the error is greater than 20% of the measured $T_{\text{kin}}$, adopting for these pixels the median $T_{\text{kin}}$ temperature of all pixels with emission in the 1.3 mm dust continuum above 3$\sigma$ (obtained from Sanhueza et al. 2019; see Table 1). In each source the $T_{\text{kin}}$ ranges from $\sim 7$ to $\sim 50$ K, showing on average mild temperature gradients that only in some rare cases reach a few tens of kelvins within the same source. We find an average error of $\sim 12\%$ $T_{\text{kin}}$, which corresponds to $\sim 2$ K.

The gas-to-dust ratio, $\gamma$, is computed following Giannetti et al. (2017a) with a gradient of $\gamma$ through the Galactic disk:

$$\log_{10}(\gamma) = 0.087 \, R_{\text{GC}} + 1.44,$$

(3)

where $R_{\text{GC}}$ is the galactocentric distance of each source expressed in kpc (Table 1 and Whitaker et al. 2017). This prescription gives values of the gas-to-dust ratio between 69 and 87 (Table 1) and represents the second modification to the procedure followed by Sanhueza et al. (2019) to derive $N(H_2)$, where $\gamma$ is taken to be 100. In the worst-case scenario, this has produced a modest difference of $30\%$ in the final $N(H_2)$, but leaving unchanged their gradient across the sources. This variation agrees with the intrinsic error of $32\%$ derived in Sanhueza et al. (2017) considering the uncertainties associated with the dust opacity and $\gamma$ in the mass determination of cores and also reflects the typical error associated with $N(H_2)$ considering the uncertainties on $T_{\text{dust}}$ (e.g., Urquhart et al. 2018; Sanhueza et al. 2019). For this reason, we refer to Sanhueza et al. (2019) for the discussion on the distribution of $N(H_2)$ in each source and for the visual inspection of the ALMA Band 6 continuum maps.

### 3.2. C$^{18}$O Column Density Maps

We derive the C$^{18}$O column density, $N(C^{18}O)$, from its $J = 2-1$ molecular transition observed with ALMA (see Section 2.1) by following Kramer & Winnewisser (1991):

$$N(C^{18}O) = \frac{3h}{8\pi^3 \mu^2} \int T_b \, dv,$$

(4)

where $f(T_{\text{ex}}^{\text{C}^{18}\text{O}}) = \frac{Z}{2} \exp \left( \frac{E_1}{k_B T_{\text{ex}}} \right) \left[ 1 - \exp \left( - \frac{h \nu_{2,1}}{k_B T_{\text{ex}}} \right) \right]^{-1}$

$$\times \left[ J(T_{\text{ex}}, \nu_{2,1}) - J(T_{\text{bg}}, \nu_{2,1}) \right]^{-1},$$

(5)

with $h$ is the Planck constant and $\mu_1$ is the beam filling factor, assumed equal to 1. In addition, $\mu = 0.112 \times 10^{-18} \, \text{dyn} \, \text{cm}^{-2}$ is the C$^{18}$O dipole moment, $Z = 0.36 \, T_{\text{ex}}^{\text{C}^{18}\text{O}} + 1/3$ is the partition function (e.g., Herzberg 1945), $E_1$ is the energy of the lower level of the transition, $T_{\text{ex}}^{\text{C}^{18}\text{O}}$ is the gas excitation temperature of C$^{18}$O, $J(T_{\text{ex}}, \nu) = (h/v_k T_{\text{ex}})(exp (h/v_k T_{\text{ex}}) - 1)^{-1}$, $T_{\text{bg}} = 2.7 \, \text{K}$ is the background temperature, and $T_p$ is the brightness temperature of the line. The integrated intensity is taken by considering the emission above the $3\sigma$ threshold in a range of $\pm 5 \, \text{km} \, \text{s}^{-1}$ around the $v_{\text{lsr}}$ reported in Table 1.

In Equation (4), $f(T_{\text{ex}}^{\text{C}^{18}\text{O}})$ incorporates all the constants and the terms that depend on $T_{\text{ex}}^{\text{C}^{18}\text{O}}$. In addition, $C^\gamma = \tau C^{18}O / [1 - \exp(-\tau C^{18}O)]$ is the optical depth correction factor, valid for $\tau \leq 2$ with uncertainty of about $15\%$ (e.g., Frerking et al. 1982; Kramer & Winnewisser 1991), where $\tau C^{18}O$ is the optical depth of the C$^{18}$O (2–1) line derived following the approach discussed in Sabatini et al. (2019) and summarized in Appendix A. All the molecular parameters are taken from the Cologne Database for Molecular Spectroscopy (CDMS; Müller et al. 2001). In each source, the 1$\sigma$ rms is computed as the average over five channels—far from the C$^{18}$O (2–1) line —of the flux’s standard deviations computed in a large region centered at the position of the source. We solve Equation (4) under the assumption of local thermodynamic equilibrium (LTE), i.e., $T_{\text{kin}}^{\text{C}^{18}\text{O}} = T_{\text{dust}} = T_{\text{ex}}^{\text{C}^{18}\text{O}}$. The only exception is G332.969-00.029, which lacks in available NH$_3$ data, and for which we assume $T_{\text{dust}} = T_{\text{ex}}^{\text{C}^{18}\text{O}} = 12.6 \, \text{K}$ as the dust temperature reported by Guzmán et al. (2015). To avoid possible overestimates of $N(C^{18}O)$, produced by too low $T_{\text{ex}}^{\text{C}^{18}\text{O}} = T_{\text{kin}}^{\text{C}^{18}\text{O}}$ values, we impose a lower limit of $T_{\text{ex}}^{\text{C}^{18}\text{O}} = 10.8 \, \text{K}$ that corresponds to the separation between the levels of the C$^{18}$O (2–1) transition. In the worst-case scenario, this prescription affects less than 6% of the pixels where $N(C^{18}O)$ is computed. The opacity-corrected column density map of C$^{18}$O, also corrected for the PB effects, is shown in Appendix A. Our correction has increased $N(C^{18}O)$ by up to a factor of about $\sim 1.8$, producing $N(C^{18}O)$ spanning the range of $(0.1-6.4) \times 10^{16} \, \text{cm}^{-2}$.

#### 3.3. Core-scale CO-depletion Maps

The final CO-depletion factor maps, shown in Figures 1 and 2, are generated as the ratio between the expected and the observed abundance of CO relative to H$_2$, following Equation (1). For each source, we derive the expected C$^{18}$O/H$_2$ abundance assuming (Frerking et al. 1982; Fontani et al. 2006; Giannetti et al. 2017a)

$$X^{C^{18}\text{O}} = \frac{9.5 \times 10^{-5} \times 10^{\alpha(R_{GC}-R_{GC,\odot})}}{16\text{O}^{18}\text{O}},$$

(6)

with $R_{GC}$ expressed in kpc, $R_{GC,\odot} = 8.34 \, \text{kpc}$ (Reid et al. 2014), and $\alpha = -0.08 \, \text{dex} \, \text{kpc}^{-1}$ describing the C/H abundance (Luck & Lambert 2011), under the assumption that the C/H abundance controls the CO formation. The oxygen isotopic ratio, $^{16}\text{O}^{18}/^{18}\text{O} = 58.8 R_{GC} + 37.1$, is computed according to Wilson & Rood (1994). We employ the galactocentric distances of the sources reported by Whitaker et al. (2017), according to Sanhueza et al. (2019). We find $X^{C^{18}\text{O}}$ between $4.1 \times 10^{-7}$ and $6.3 \times 10^{-7}$ (see Table 1).

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Note that the C/H abundance is given in dex units, which introduces the term $10^{\alpha}$ in Equation (6).
Figure 1. $f_D$ maps obtained following the procedure explained in Section 3.3, in six of the twelve ASHES clumps (i.e. G010.991–00.082, G014.492–00.139, G028.273–00.167, G327.116–00.294, G331.372–00.116, G332.969–00.029). The cores identified in Sanhueza et al. (2019) are shown as orange and red contours for prestellar and protostar cores, respectively, following the classification in Section 2.1. The ALMA synthesized beams are displayed in red in the lower left corner of each panel, while the scale bar is shown in the lower right corners. The color wedge of each panel displays the color scales corresponding to $f_D$ in the log-scale.
In each \( f_D \) map (Figures 1 and 2) we also report as orange/red regions the cores identified in Sanhueza et al. (2019): orange for the prestellar stage and red for the protostellar one (see Section 2). The degree of depletion reveals widely different chemical conditions within the individual clumps. It spans regions where CO adsorption is almost irrelevant, with observed abundances of \(^{13}\text{CO}\) as expected (i.e., \( f_D = 1 \)), up to regions where only less...
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C18O within those cores.

Furthermore, we can also see a weak temperature effect when keeping the desorption process, it is reasonable that the evolution of the population of protostellar cores (i.e., 25 protostellar vs. 12 prestellar cores), shows CO depletion that is comparable to (and in some cases higher than) clumps dominated by prestellar cores (e.g., G028.273–00.167 and G340.222–00.167; Figures 1 and 2, respectively). This can be explained by exploring the physical conditions in the clumps. Due to the absence of protostars and outflows that can heat the gas surrounding the cores, these young clumps reveal mild temperature gradients.

In the 12 sources shown in Figures 1 and 2, the behavior of $f_D$ follows an unexpected increase as the evolution of the cores progresses, i.e., going from pre- to protostellar (see Table 2). As an example, G014.492–00.139 (Figure 1), with a large population of prestellar cores (i.e., 25 protostellar vs. 12 prestellar cores), shows CO depletion that is comparable to (and in some cases higher than) clumps dominated by prestellar cores (e.g., G028.273–00.167 and G340.222–00.167; Figures 1 and 2, respectively). This can be explained by the absence of protostars and outflows that can heat the gas surrounding the cores, these young clumps reveal mild temperature gradients. Looking at the regions associated with a $>3\sigma$ continuum emission, G028.273–00.167 and G340.222–00.167 show a $\Delta T_{\text{kin}}^{\text{NH}_3} \sim 1$ and $\sim 3$ K, respectively. If we then neglect the effect of temperature on the desorption process, it is reasonable that the evolution of the averaged $f_D$ is mainly density driven. This is confirmed by the results reported in Figure 4(a), which show the depletion factor as a function of both density and temperature. This result also seems independent of the heliocentric distance associated with each ASHES clump, as discussed in Appendix B. From the same figure we can also see a weak temperature effect when keeping the density constant, due to the weak temperature gradients in the $T_{\text{kin}}^{\text{NH}_3}$ maps (see also Figure 4(b)).

Note. Some of the cores identified in dust continuum are not associated with a value of $f_D$ (see, e.g., G010.991–00.082 and G327.116–00.294 in Figure 1). However, around those peculiar regions we find $f_D$ among the highest over the entire clump. Thus, we expect extremely low abundances of $^{13}$CO within those cores (therefore high $f_D$), below the limit of detection accessible to our observations (Table 1).

Within an evolutionary picture, clumps dominated by protostellar conditions are characterized by densities on average larger than the prestellar ones (e.g., König et al. 2017; Elia et al. 2021 and Urquhart et al. 2022). The same evolutionary trend is also seen at core scales (Sanhueza et al. 2019). In addition, all
the sources have been selected as 70 μm dark, and it is conceivable that the embedded protostars are at their early stages, i.e., yet to heat the surrounding gas significantly. It is then likely that the high degree of CO depletion is associated with the envelopes of these young protostellar objects, where protostellar activity has not yet led to a significant desorption of the frozen-out CO.

In Figure 5 we show the distributions of $f_D$ for the entire population of pre- and protostellar cores in our sample (blue and orange histograms, respectively). The former show a median $f_D$ of 8.5, while in the protostellar population we derive a median of 12.2. The protostellar distribution on average looks shifted toward higher values compared to the prestellar distribution, confirming what we observe in the maps, as well as in individual clumps (see Appendix B). This result is confirmed by a Kolmogorov–Smirnov (K-S) test (Massey 1951). The test yields a $p$-value $< 2 \times 10^{-3}$, which is lower than the statistical significance level of 5% usually adopted to reject the hypothesis that the two data sets come from the same continuous distribution (e.g., Teegavaramu 2019).

4. Discussion

The study of CO depletion in high-mass star-forming regions has been pursued over the years at different scales via both observations and theoretical studies. For example, the global distribution of $f_D$ reported in Figures 1 and 2 is in agreement with the most recent state-of-the-art three-dimensional numerical simulations presented by Bovino et al. 2019, where the authors have simulated the collapse of turbulent and magnetized isothermal cores, exploring different initial conditions. They reported $f_D$ values between 50 and 100 on a scale of 2000 au (the effective radius associated with many of the cores identified in ASHES; Sanhueza et al. 2019), qualitatively in line with our ALMA data. Notably, the values reported by Bovino et al. (2019) have been convolved with an ALMA-like point-spread function, showing a loss in the final $f_D$ of a factor up to three when compared to the original simulated cubes. This might suggest the presence of compact regions where the chemistry of the CO is dramatically influenced by extreme freeze-out conditions not recoverable with our angular resolution.

On the observational side, however, a rigorous comparison with previous results is challenging, since most of the estimates of $f_D$, whether derived from single-point spectra (e.g., Thomas & Fuller 2008; Fontani et al. 2012; Giannetti et al. 2014) or maps (e.g., Hernandez et al. 2011; Pon et al. 2016; Feng et al. 2016a, 2020; Sabatini et al. 2019 and Gong et al. 2021), are obtained at scale-clip angular resolutions. Very few exceptions have been reported for high-mass star-forming regions (see Zhang et al. 2009; Morii et al. 2021; Rodríguez et al. 2021). Within this context our results represent the first core-scale interferometric $f_D$ maps observed with ALMA for a sample of high-mass clumps.

In the specific case of ASHES, Morii et al. (2021) estimated $f_D$ using additional $^{18}$CO (2–1) ASHES data observed in the 70 μm dark IRDC G023.477+0.114. This source is not included in this work and in the pilot study published in Sanhueza et al. (2019). G023.477+0.114 has a near-kinematic distance of 5.2 ± 0.5 kpc, which implies a linear-scale resolution of $\sim$5900 au, comparable with those of the data presented in Section 2.1. The authors consider a variation of $X_{^{18}\text{CO}}$ with the galactocentric distance of the source and constant values for $\gamma = 100$. They report average $f_D$ values between ~40 and 300 through the 11 cores at different evolutionary stages identified in G023.477+0.114. Notably, also in this case, $f_D$ does not decrease going from the prestellar to the protostellar stage and shows extreme values of $f_D > 100$ associated with the most evolved sources, in agreement with our findings.

Zhang et al. (2009) conducted 1.3 mm spectral line and continuum observations of two massive molecular clumps harbored in the IRDC G28.34+0.06 (Pillai et al. 2006; Wang et al. 2008). The $^{13}$CO (2–1) line was observed with the Submillimeter Array (SMA; Ho et al. 2004) telescope at a resolution of 0.72 and with a final sensitivity of 90 mJy beam$^{-1}$ at the spectral resolution of 1.2 km s$^{-1}$. This angular scale corresponds to $\sim$4500 au at the source heliocentric distance of 4.5 kpc (Urquhart et al. 2018), similar to the physical scales mapped in our ALMA observations. In each clump, the continuum dust emission at 1.3 mm has revealed multiple cores with typical sizes of $\sim$5000 au. However, out of these cores only one shows a clear detection with an averaged value of $f_D \sim 100$ (Zhang et al. 2009). The authors assumed $\gamma = 100$ and $X_{^{18}\text{CO}} = 5 \times 10^{-9}$. If we rescale the $f_D$ found for G28.34+0.06, assuming a galactocentric distance of 4.8 kpc in Equations (3) and (6), we obtain an $f_D \sim 45$, which is in line with the range of values reported in Figure 3. Similarly, Rodríguez et al. (2021) observed the $^{18}$CO (2–1) line toward the high-mass protostellar candidate ISOSS J2035+5953 SMM2 with SMA at $\sim$2″5 ($\sim$10 au at the distance of 4.3 kpc). They report $f_D \sim 20$, already considering the variation of $\gamma$ and $X_{^{18}\text{CO}}$ with galactocentric distance of the source ($\sim$10 kpc Bosco et al. 2019).

It is worth noting that both the sources of Zhang et al. (2009) and Rodríguez et al. (2021) host mYSOs as demonstrated by

\[ \text{Taking a brightness temperature of 2.5 K, an FWHM of 2.5 km s}^{-1}, \text{a gas temperature of 30 K as reported by Zhang et al. (2009) for the detected C^{18}O (2–1) line, and the derived } \gamma = 72 \text{ and } X_{^{18}\text{CO}} = 5.7 \times 10^{-7}. \]
respectively. This result confirms the reliability of \( f_D \) to classify high-mass clumps at different evolutionary stages, as found in several samples (e.g., Fontani et al. 2012; Giannetti et al. 2014; Sabatini et al. 2019). The different behavior of \( f_D \) observed at clump and core scale might be the consequence of the complex interplay between chemistry and physics and their associated timescales. In particular, the chemical response to physical changes is smeared out when looking at clump scales, reflecting the average properties of the entire population of cores.

5. Conclusions

In this paper we presented the first core-scale \( f_D \) maps derived from \( \text{C}^{18}\text{O} \) (2–1) and 1.3 mm continuum ALMA observations for the 12 70 \( \mu \)m dark clumps of the ASHES sample. In this context, we have discussed whether the averaged CO-depletion factor computed at core scales can be considered a reliable evolutionary indicator of the high-mass star formation process.

The overall scenario that emerged from this study shows peculiar chemical conditions for the ISM involved in our targets, which changes according to the physical scale investigated. On the clump scale, we find that on average at least half of the expected CO has been removed from the gas phase, for more than 85% of the total area mapped in \( \text{C}^{18}\text{O} \). The highest values of CO depletion are found within the identified cores (both pre- and protostellar), where \( f_D \) values of more than 10 are reached in more than \( \sim 50\% \) of the cores.

In contrast to what has been observed for low-mass star-forming cores and, more generally, for high-mass clumps that have the potential to form high-mass stars, our analysis shows that the degree of the CO-depletion process on core scales does not decrease during the transition from a prestellar to a protostellar phase. If we exclude the temperature effect due to the slight gradients in the \( T_{\text{kin}} \) maps, we explain the evolutionary behavior of \( f_D \) as primarily dependent on the average gas density, which increases with the evolution of the cores. This effect is not observed in the low-mass regime since the high-density regions have smaller sizes and are more affected by temperature variations driven by the star formation process. Furthermore, low-mass star-forming regions are also statistically closer to the solar system, allowing for a better linear resolution. We emphasize that, due to the poorer resolution of the \( \text{NH}_3 \) maps (on average a factor \( \sim 4 \) coarser) compared to those of \( \text{C}^{18}\text{O} \), temperature is also one of the main uncertainties affecting our results. Our analysis could greatly benefit from ammonia observations with a resolution comparable to that of ALMA. Nevertheless, we highlight the significant improvement for having derived temperatures at \( \sim 5" \) angular resolution with respect to adopting the Herschel dust temperatures at 35" resolution.

The \( f_D \) fluctuations appear to be widely distributed when observed over thousands of astronomical units, and in particular they trace the densest regions of clumps that are not always associated with a prestellar core. Our results lead us to classify \( f_D \) as a tracer that is not entirely reliable to distinguishing between prestellar and protostellar cores in high-mass star-forming clumps. However, thanks to the high CO-depletion factors found in large parts of the clump, a more

Figure 6. Correlation between \( f_D \) and the luminosity-to-mass ratio of the clumps that compose the ASHES sample. Yellow circles are associated with each source, while uncertainties are shown as black bars. The red dashed line represents the linear least-squares fit of \( f_D \) to the log_{10}(L/M). The fit parameters are shown in the legend, with Spearman’s rank correlation coefficient \( \rho_s = -0.62 \) and a p-value = 0.03.
complete picture of evolution can be obtained by observing deuteron molecules. The abundance of ortho-H₂D⁺, for example, has been asserted as a clear chemical indicator of prestellar stages both at the clump scale (e.g., Giannetti et al. 2019; Miettinen 2020 and Sabatini et al. 2020) and at the core scales by the recent results of Redaelli et al. (2021) and Redaelli et al. (2022) obtained from ALMA data. Improving the sensitivity of astronomical facilities in the millimeter and submillimeter regime (such as APEX and ALMA) and the systematic study of deuteron molecules (such as H₂D⁺ and D₂H⁷⁺) therefore seems to be the necessary breakthrough to finally obtain a comprehensive picture of the process of high-mass star formation.

The authors thank the anonymous referee, for her/his suggestions to improve the manuscript. G.S. gratefully acknowledges financial support by the ANID BASAL project FB210003 and Dr. R. Pascale for fruitful discussions. S.B. is financially supported by ANID Fondecyt Reguler (project No. 1220033) and the ANID BASAL projects ACE210002 and FB210003. P. S. was partially supported by a Grant-in-Aid for Scientific Research (KAKENHI Nos. 18H01259 and 22H01271) of the Japan Society for the Promotion of Science (JSPS), K.T. was supported by JSPS KAKENHI (grant No. 20H05645). This paper makes use of the ALMA data ADS/JAO.ALMA#2015.1.01539.S (PI: P. Sanhueza). ALMA is a partnership of ESO (representing its member states), NSF (USA) and NINS (Japan), together with NRC (Canada), MOST and ASIAA (Taiwan), and KASI (Republic of Korea), in cooperation with the Republic of Chile. The Joint ALMA Observatory is operated by ESO, AUI/NRAO and NAOJ.

Facility: The Atacama Large Millimeter/submillimeter Array (ALMA; Wooten & Thompson 2009).

Software: This research has made use of PySpecKit (https://bitbucket.org/), ASTRODENDRO (https://dendrograms.readthedocs.io/en/stable/), a Python package to compute dendrograms of Astronomical data), APLpy (an open-source plotting package for Python; Robitaille & Bressert 2012), Astropy (https://www.astropy.org/; Astropy Collaboration et al. 2013, 2018), NumPy (Harris et al. 2020), Maplotlib (Hunter 2007), the Cologne Database for Molecular Spectroscopy (CDMS), and NASA’s Astrophysics Data System Bibliographic Services (ADS).

Appendix A

C¹⁸O Opacity Correction

When deriving the N(C¹⁸O), it is worth inspecting whether the emission of C¹⁸O (2–1) can be assumed to be optically thin. The optical depth of a transition can be estimated through the peak ratio of the same transition, coming from different isotopologues, if their relative abundance is known (e.g., Hofner et al. 2000). We computed τC¹⁸O using C¹⁷O (2–1), C¹⁸O (2–1), and H₂ data published in Feng et al. (2020) observed in G014.492–00.139, and we refer to this paper for a more detailed description of the data set. We selected this source since the final N(H₂) are among the highest of the entire ASHES sample, and therefore G014.492–00.139 represents an ideal case to study the variation of τC¹⁸O.

Assuming equal excitation temperatures and filling factor for the two species, τC¹⁸O is estimated as

\[
R_{18,17} = \frac{\tau_{C^{18}O \text{mb}}}{\tau_{C^{17}O \text{mb}}} \propto \frac{[1 - \exp(-\tau_{C^{18}O})]}{[1 - \exp(-\tau_{C^{17}O})]},
\]

where \(\tau_{C^{17}O}\) is the optical depth of C¹⁷O (2–1) at ~224.7 GHz, for which we assume \(\tau_{C^{17}O} = \tau_{C^{17}O}/4.16\) (e.g., Wouterloot et al. 2008). This is performed pixel by pixel for both C¹⁷O and C¹⁸O data cubes by taking data where both the continuum and the line emission have a >3σ level detection. We employ the Python Spectroscopic Toolkit (PySpecKit; Ginsburg & Mirocha 2011; Ginsburg et al. 2022), by using a single Gaussian component over a velocity space of ±3 km s⁻¹ around the local standard of rest velocities \(\langle V_{lsr}\rangle\) derived in Sanhueza et al. (2019). The estimated \(\tau_{C^{17}O}\) are in the range of ~0.25–1.80, implying optical depth correction factors \(C_\tau \sim \{1.13–2.16\}\) to derive the final \(N(C^{18}O)\) from Equation (4). In more than 75% of the sources detected in C¹⁸O, \(\tau_{C^{18}O} < 1.37\) \((C_\tau < 1.84)\). Similar \(\tau_{C^{17}O}\) are also reported in other IRDCs (e.g., Sanhueza et al. 2010; Sabatini et al. 2019; Gong et al. 2021), proving that C¹⁸O is virtually always optically thin under the typical conditions prevalent in IRDCs.

To account for the same correction in the other ASHES sources, we follow the same approach as Sabatini et al. (2019), looking for a linear relation between \(\log_{10}(\tau_{C^{18}O})\) and \(\log_{10}[N(H_2)]\). We have preferred the H₂ column density over \(N(C^{18}O)\) since \(N(H_2)\) is not affected by opacity at the observed size scales (i.e., \(\kappa_\nu\) correction already applied in Section 3.1). The final C¹⁸O column density maps (see Figures 7 and 8) are derived applying in each source the best-fit \(\log_{10}(\tau_{C^{18}O}) - \log_{10}[N(H_2)]\) relation obtained in G014.492–00.139, i.e., \(\log_{10}(\tau_{C^{18}O}) = 0.6\log_{10}[N(H_2)] - 14.4\).
Figure 7. Final $N$(C$^{18}$O) maps obtained following the procedure explained in Section 3.2, in six of the twelve ASHES clumps (i.e. G010.991–00.082, G014.492–00.139, G028.273–00.167, G327.116–00.294, G331.372–00.116, G332.969–00.029). All the maps are corrected for opacity effects as reported in Appendix A. Green contours correspond to the ALMA dust continuum emission at $[3.9, 27] \times \sigma$ (Sanhueza et al. 2019). The ALMA synthesized beams are displayed in red in the lower left corner of each panel, while the scale bar is shown in the lower right corners. The color wedge of each panel displays the color scales corresponding to $N$(C$^{18}$O) in the log-scale.
Figure 8. Same as Figure 7 for the remaining six ASHES clumps (i.e. G337.541-00.082, G340.179-00.242, G340.222-00.167, G340.232-00.146, G341.039-00.114, G343.489-00.416).
Appendix B

Notes on the Analysis for Individual Clumps

The aim of this section is to test the influence of some specific properties of the clumps on the results discussed in Sections 3.3 and 4 (e.g., the heliocentric distance of the clumps, the number of cores, or the proportion of pre- and protostellar cores found in each ASHES source).

Figure 9 represents the analog of Figure 4, in which we have colored the cores as a function of the heliocentric distance of the clumps hosting them. There is no clustering of cores when the distance of each source is considered, and the cores associated with each distance bin span comparable ranges of values in terms of $f_D$ and $n$(H$_2$), corresponding to at least a factor of $\sim 5$. Thus, the distribution of cores shown in Figure 4 appears to be distance independent, ruling out the influence of a possible distance bias on our results.

Figure 10 represents the analog of Figure 5 and shows the number distributions of the averaged $f_D$ associated with ASHES cores within each clump separately. Although the statistics of the cores in each clump is greatly reduced compared to the total number of cores shown in Figure 5, we note that the median value of $f_D$ derived for the prestellar population of cores (blue vertical lines in Figure 10) is always lower than—or at most equal to—the value found for the protostellar cores (red dashed vertical lines; Figure 10). Figure 10 also shows that randomly removing a clump from the analysis presented in Sections 3.3 and 4 does not qualitatively change the general conclusions summarized in Section 5.

Figure 9. Same as Figure 4(a), but showing the variation in the average $f_D$ and $n$(H$_2$) for the core population identified in ASHES as a function of the heliocentric distance of each clump (indicated in the color wedge; see also Table 1). Circles and squares represent the prestellar and protostellar cores, respectively.
Figure 10. Same as Figure 5, but showing the number distributions of the averaged $f_D$ associated with each core identified in ASHES. In the different panels, the distributions within each clump are shown separately (red labels in the upper left corners). The blue and orange histograms refer to prestellar and protostellar cores, respectively. The vertical lines represent the median of $f_D$ resulting from the distributions of prestellar (blue lines) and protostellar (red dashed lines) cores.
Teegavarapu, R. S. 2019, in Trends and Changes in Hydroclimatic Variables, ed. R. Teegavarapu (Amsterdam: Elsevier), 1, https://www.elsevier.com/books/trends-and-changes-in-hydroclimatic-variables/teegavarapu/978-0-12-810985-4

Thomas, H. S., & Fuller, G. A. 2008, A&A, 479, 751

Tigé, J., Motte, F., Russeil, D., et al. 2017, A&A, 602, A77

Urquhart, J. S., Hoare, M. G., Purcell, C. R., et al. 2009, A&A, 501, 539

Urquhart, J. S., König, C., Giannetti, A., et al. 2018, MNRAS, 473, 1059

Urquhart, J. S., Wells, M. R. A., Pillai, T., et al. 2022, MNRAS, 510, 3389

Wang, K., Zhang, Q., Testi, L., et al. 2014, MNRAS, 439, 3275

Wang, Y., Zhang, Q., Pillai, T., Wyrowski, F., & Wu, Y. 2008, ApJL, 672, L33

Whitaker, J. S., Jackson, J. M., Rathborne, J. M., et al. 2017, AJ, 154, 140

Wiles, B., Lo, N., Redman, M. P., et al. 2016, MNRAS, 458, 3429

Wang, K., Zhang, Q., Testi, L., et al. 2014, MNRAS, 439, 3275

Wilson, T. L., & Rood, R. 1994, ARA&A, 32, 191

Wilson, W. E., Ferris, R. H., Axtens, P., et al. 2011, MNRAS, 416, 832

Wootten, A., & Thompson, A. R. 2009, IEEE Proc., 97, 1463

Wouterloot, J. G. A., Henkel, C., Brand, J., & Davis, G. R. 2008, A&A, 487, 237

Zhang, Q., & Wang, K. 2011, ApJ, 733, 26

Zhang, Q., Wang, Y., Pillai, T., & Rathborne, J. 2009, ApJ, 696, 268

Zhang, Y., Tan, J. C., & Hosokawa, T. 2014, ApJ, 788, 166

Zwillinger, D., & Kokoska, S. 2000, CRC Standard Probability and Statistics Tables and Formulae (Boca Raton, FL: CRC Press), http://tomlr.free.fr/Mathematiques/Math%20Complete/Probability%20and%20Statistics/CRC%20-%20standard%20probability%20and%20statistics%20tables%20and%20formulae%20-%20DANIEL%20ZWILLINGER.pdf