Possible Habitats for NH3, NH2D, H13CN, HC15N, SO, and C18O in the Initial Conditions of High-mass Star Formation (Postprint)

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Abstract

The initial condition of high-mass star formation is a complex area of study because of the high densities () and low temperatures (Tdust $<$ 18 K) involved. Under such conditions, many molecules become depleted from the gas phase by freezing out onto dust grains. However, the N-bearing and deuterated species could remain gaseous under these extreme conditions, suggesting that they may serve as ideal tracers. In this paper, using the Plateau de Bure Interferometer and Very Large Array observations at 1.3 mm, 3.5 mm, and 1.3 cm, we investigate the possible habitats for NH3, NH2D, H13CN, HC15N, SO, and C18O in eight massive precluster and protocluster clumps G18.17, G18.21, G23.97N, G23.98, G23.44, G23.97S, G25.38, and G25.71. We found that the NH3 cores are in good agreement with the 3.5 mm peak emission, but the NH3 is much more extended than the 3.5 mm emission structure. The SO distributions agree well with the 3.5 mm peaks for the evolved star formation stage, but we did not detect any SO emission in the four earliest star formation sources. C18O is a poor tracer in conditions of the cold (18 K) and dense (104 cm−3) cores, e.g., the prestellar cores. We also found that the NH2D cores are mainly located in the temperature range of 13.0–20.0 K, and the NH2D lines may be strongly depleted above 20 K.

Full Text

Preamble

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Possible Habitats for NH3, NH2D, H13CN, HC15N, SO, and C18O in the Initial Conditions of High-mass Star Formation

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Abstract

The initial conditions of high-mass star formation represent a complex area of study because of the high densities ($\geq 10^4$ cm^{-3}) and low temperatures (Tdust < 18 K) involved. Under such conditions, many molecules become depleted from the gas phase by freezing out onto dust grains. However, N-bearing and deuterated species could remain in the gas phase under these extreme conditions, suggesting that they may serve as ideal tracers. In this paper, using Plateau de Bure Interferometer and Very Large Array observations at 1.3 mm, 3.5 mm, and 1.3 cm, we investigate the possible habitats for NH3, NH2D, H13CN, HC15N, SO, and C18O in eight massive precluster and protocluster clumps: G18.17, G18.21, G23.97N, G23.98, G23.44, G23.97S, G25.38, and G25.71. We find that the NH3 cores are in good agreement with the 3.5 mm peak emission, but the NH3 is much more extended than the 3.5 mm emission structure. The SO distributions agree well with the 3.5 mm peaks for evolved star formation stages, but we did not detect any SO emission in the four earliest star formation sources. C18O is a poor tracer under cold (\$ $18K)anddense($ 10^4\$ cm^{-3}) core conditions, such as in prestellar cores. We also find that the NH2D cores are mainly located in the temperature range of 13.0–20.0 K, and the NH2D lines may be strongly depleted above 20 K.

Key words: galaxies: star formation -techniques: interferometric -methods: observational

1. Introduction

High-mass star formation, involving masses greater than 8 M$_\odot$, dominates the environment and evolution of the Galaxy. However, there remains a significant lack of knowledge about how high-mass stars form in their early stages (e.g., Pillai et al. 2007, 2011, 2012; Motte et al. 2018; Zhang et al. 2019, 2020). Particularly, the transition from a prestellar core to a protostar has not been well studied observationally due to the short lifetime of the prestellar stage, the difficulty in determining the relative evolutionary stage of objects, the small spatial scales involved, and the lack of strong molecular tracers for cores at high densities and low temperatures (Friesen et al. 2014). At the high densities ($\geq 10^4$

cm^{-3}) and low temperatures (Tdust < 18 K) characteristic of the interiors of highly evolved star-forming cores, many molecules deplete from the gas phase by freezing onto dust grains (Walmsley et al. 2004; Bergin & Tafalla 2007), including the dense gas tracer C18O (Zhang et al. 2017). However, some N-bearing species are good tracers of dense gas and cold conditions in initial star formation. In addition, the deuterium fractionation of remaining gas-phase species increases dramatically above the cosmic abundance ratio ($[\mathrm{D/H}] \sim 1.5 \times 10^{-5}$; Oliveira et al. 2003) due to increased production of H2D+ by the reaction of H3+ with HD in regions where CO is depleted (Roberts & Millar 2000).

The elements C, N, O, and S, produced by nucleosynthesis in stars, are important components in early Galactic star formation (e.g., Wilson & Rood 1994; Wielen & Wilson 1997; Ikeda et al. 2002). The abundances of C, N, and O may contain important information not only about the history of nucleosynthesis but also about the earliest stages of star formation. Understanding their precise content in local interstellar clouds is of fundamental importance in astrophysics and astrochemistry (e.g., Gerner 2014; Gerner et al. 2015). These elements have been widely observed in many different observations, such as in the form of CO, SO, HCN, and NH3 (e.g., Zhang et al. 2014, 2017). However, their isotopic species, such as SO, H13CN, HC15N, and NH2D (e.g., Daniel et al. 2016; Booth et al. 2019; Li et al. 2024), are rarely studied in detail during the early stages of massive star formation.

Investigating different molecular tracers in various star formation environments helps us understand how to select and use appropriate tracers to study particular star formation conditions. Thus, in this paper we investigate the possible habitats for NH3, NH2D, H13CN, HC15N, SO, and C18O associated with the early stages of high-mass star formation. Section 2 presents the observations and data reduction. Section 3 presents the observational results and analysis for the 3.5 mm continuum emission and NH3, NH2D, H13CN, HC15N, SO, and C18O spectra. Section 4 discusses possible habitats for NH2D and the other N-bearing species, and Section 5 provides a summary.

2.1. General Observational Information

The IRAM Plateau de Bure Interferometer (PdBI) and National Radio Astronomy Observatory (NRAO) Very Large Array (VLA) observations in the 1.3 mm, 3.5 mm, and 1.3 cm continuum toward the clumps G18.17, G18.21, G23.97N, G23.98, G23.44, G23.97S, G25.38, and G25.71 have been described and presented in Zhang et al. (2019). The NH2D 111-101 (at 85.926 GHz), NH3 (1, 1), and (2, 2) observations have been presented in Zhang et al. (2020). Here, the spectral observations and data for H13CN, HC15N, SO, and C18O, combined with the above data, are further described and exhibited. In this paper, we use only the 3.5 mm continuum data to trace dense cores in the clumps. The 1.3 cm continuum data, which mainly trace free-free emission, are not used, and the 1.3 mm continuum data, which have relatively smaller effective regions and lower sensitivity than the 3.5 mm data, are also not used in this work.

2.2. PdBI Observations

The spectra in the PdBI observations were observed simultaneously with the continuum but with separate correlator windows. In receiver 1, NH2D (85.926 GHz) and H13CN (86.340 GHz) were each tuned to a 40 MHz bandwidth with 460 channels, providing a velocity resolution of 0.27 km s^{-1} per channel. HC15N (86.055 GHz) and SO (86.094 GHz) were tuned to the same 80 MHz bandwidth with 230 channels, providing a velocity resolution of 1.09 km s^{-1} per channel. In receiver 2, C18O (219.560 GHz) was tuned to an 80 MHz bandwidth with 230 channels, providing a velocity resolution of 0.43 km s^{-1} per channel. The rms noise of the spectra was about 23 mJy $beam^{-1}$ for NH2D on the CD track and about 12 mJy $beam^{-1}$ for NH2D on the BCD track. In this work, we used only the observational data from the CD track.

The IRAM software package GILDAS was utilized for spectral reduction. The region of a double primary beam was searched for cleaning components, and no polygon was introduced to avoid biased cleaning. The primary beam is 58.5”and 23.0” at 86.086 and 219.560 GHz, respectively. The data have been corrected for primary beam attenuation. More details are presented in Zhang et al. (2019, 2020).

3. Observational Results and Analysis

For the eight clumps G18.17, G18.21, G23.97N, G23.98, G23.44, G23.97S, G25.38, and G25.71, the maps for NH3, NH2D, H13CN, HC15N, SO, C18O, and the 3.5 mm continuum emission are shown in the Appendix, while the maps for kinetic temperature and column density can be found in Zhang et al. (2019, 2020). The clumps G18.17, G18.21, G23.97N, and G23.98 are in an early star formation or prestellar stage, while the clumps G23.44, G23.97S, G25.38, and G25.71 are in an evolved star formation or protostar stage (Zhang et al. 2019). We use the function `scipy.stats.binned_{statistic}()` in Python to examine pixel-by-pixel relationships between the tracers NH3, NH2D, H13CN, HC15N, SO, and C18O and the 3.5 mm continuum emission, kinetic temperature, and column density. Each parameter space (from minimum to maximum) is divided into 20 bins. The minima and maxima of each parameter space are shown in Figures 2–8, where we plot some relationships of the tracers. In these figures, the integrated intensities for NH3, NH2D, H13CN, HC15N, SO, and C18O represent averaged values in each bin, while the 3.5 mm continuum emission, kinetic temperature, and column density are relative values that have been normalized. The correlations for each tracer are discussed below.

3.1. NH3 (1, 1) and (2, 2)

We present an example of NH3 (1, 1) and (2, 2) spectra in Figure 1 [Figure 1: see original paper] and integrated intensity maps in the Appendix. We primarily use the NH3 data to trace the distributions of column density and kinetic temperature in dense cores, with detailed calculations introduced in Zhang et al. (2019, 2020). Furthermore, Zhang et al. (2020) presented optical depth relations between NH2D and NH3 (1, 1). Most NH3 (1, 1) cores have optical depths ranging from 1.5 to 9, indicating that these molecular clouds are often optically thick in NH3 (1, 1). The optical depth of NH2D ranges from 0.1 to 9.7, with most values greater than 1, indicating that NH2D is also typically optically thick in dense and cold cores. Figures 2 and 3 show that relationships between NH3 (1, 1), (2, 2) and the 3.5 mm continuum emission and column density are positively correlated for most sources, though no obvious relationship exists between NH3 (1, 1), (2, 2) and kinetic temperature. In Figures A1 and A2, we see that the NH3 peak positions are well consistent with those of the 3.5 mm emission, but NH3 is much more extended than the 3.5 mm emission structure, indicating that NH3 (1, 1) and (2, 2) distributions are more extended than the 3.5 mm emission distributions.

3.2. NH2D at 85.926 GHz

We present NH2D integrated intensity maps in the Appendix. Zhang et al. (2020) found that NH2D cores are in a colder state than continuum cores, with most NH2D cores having temperatures between 13 and 17 K and only a few having kinetic temperatures above 20 K. It is likely that these cores with $ $20 K are just ahead of deeply embedded cores with $ $20 K along the line of sight. The derived kinetic temperatures may be contaminated by background emission, and NH2D may be tracing only the envelope of cores with $ $20 K. Therefore, NH2D lines may be depleted above 20 K. Comparing column densities between NH2D and continuum cores, we find that NH2D distributions are in a relatively diffuse condition compared to continuum cores, suggesting that NH2D may be a good tracer of prestellar cores. Figure 4 shows an anti-correlation between NH2D and kinetic temperature, though positive correlations exist for sources G18.17, G23.44, and G18.21, while the relationship is not obvious for other sources. Additionally, the relationship between NH2D and the 3.5 mm continuum is not obvious, but there is a weak positive correlation between NH2D and column density. Possible reasons for these trends are discussed in detail in Section 4.1.

3.3. H13CN at 86.340 GHz

H13CN often traces dense and cold cores. Its spectra have three hyperfine structure (HFS) lines (see Figure 1) (Csengeri et al. 2011; Padovani et al. 2011). The H13CN spectra of the most massive core among the 3.5 mm continuum cores are shown in Figure 1. Figure 5 [Figure 5: see original paper] reveals that relationships between H13CN integrated intensity and the related 3.5 mm continuum emission, kinetic temperature, and NH3 column density distributions are positively correlated for most sources. The integrated intensity contours are superimposed on the 3.5 mm emission image in Figure A5, showing that H13CN emission is compact and surrounds the 3.5 mm emission. It is likely that H13CN traces dense and cold cores associated with the 3.5 mm emission.

3.4. HC15N at 86.055 GHz

The HC15N spectra of the most massive core among the 3.5 mm continuum cores are shown in Figure 1. The integrated intensity contours are superimposed on the 3.5 mm emission image in Figure A6. The HC15N distributions are well consistent with the 3.5 mm peaks. The cores within clumps G23.44, G23.97S, G25.38, and G25.71 are more evolved than those in clumps G18.17, G18.21, G23.97N, and G23.98, and the most massive cores have relatively higher temperature conditions than surrounding cores (Zhang et al. 2019). Therefore, HC15N traces evolved conditions, and HC15N emission distributions are concentrated close to warmer regions within each source. Figure 6 [Figure 6: see original paper] shows that relationships between the related 3.5 mm continuum, NH3 column density distributions, and HC15N integrated intensity are positively correlated for most sources, but we cannot see a correlation between kinetic temperature and HC15N integrated intensity. This indicates that HC15N is not a good temperature tracer.

3.5. SO at 86.094 GHz

The SO spectra of the most massive core among the 3.5 mm continuum cores are shown only for sources G23.44, G23.97S, G25.38, and G25.71 in Figure 1, because we did not detect any SO emission in the other four sources. The integrated intensity contours are superimposed on the 3.5 mm emission image in Figure A7. The SO distributions are well consistent with the 3.5 mm peaks, except that the peak for G25.38 is offset from the 3.5 mm emission. This molecule appears to be less confined to small regions than others. Figure 7 [Figure 7: see original paper] shows an obvious positive correlation between SO integrated intensity and the 3.5 mm continuum distributions, though no obvious relationships are seen for kinetic temperature and column density.

3.6. C18O at 219.560 GHz

The C18O spectra of the most massive core among the 3.5 mm continuum cores are shown in Figure 1. C18O emissions are superimposed on the 3.5 mm continuum in Figure A8, where the primary beam of C18O is indicated by the dotted circle. Most C18O emission appears at or near the 3.5 mm peaks due to warmer or more evolved conditions there. It is quite rare for NH2D cores to be located at C18O emission positions. Therefore, C18O is susceptible to severe depletion at low temperatures ($ 20*K*)*andhighdensities.Figure*8[*Figure*8 : *seeoriginalpaper*]*showsapositivecorrelationbetweenC*18*Ointegratedintensityandcolumndensitydistribution* cm^{-3}) and warm ($ $20 K) star formation regions.

4.1. NH2D Distribution

NH2D may form through different chemical pathways. Deuterated ions trace hydrogen in ammonia in the gas phase, and in cold regions ($ $20 K), H2D+

reacts with NH3 to generate NH2D (e.g., Rodgers & Charnley 2001; Caselli et al. 2008; Caselli & Ceccarelli 2012; Ceccarelli et al. 2014). Li et al. (2024) presented NH2D mapping in a sample of 24 late-stage massive star-forming regions using the IRAM 30 m telescope and found that NH2D emissions have complex distributions. They suggest that dense gas (or gas density) may not be an important physical parameter affecting NH2D enhancement in these targets compared with other parameters (such as temperature), though this may be biased due to their limited spatial resolution and sensitivity.

In this work, we found that NH2D cores have quite narrow line widths, with half below 1.0 km s^{-1} (see Zhang et al. 2020), indicating very small velocity dispersion. Little NH2D emission is detected toward continuum cores, but we detected NH3 lines for most cores (see Figure A4). Based on this, we can compare velocity dispersion between NH2D and continuum cores (see Zhang et al. 2019, 2020). We found that continuum cores have larger velocity dispersion than NH2D cores. The thermal broadening of spectra is very small at rotational temperatures below 20 K, so the turbulent conditions in NH2D cores are relatively quiescent.

For the eight sources in Figures A1 and A3, we superimposed NH2D and NH3 contours on the 3.5 mm continuum. We found that NH2D peaks are not associated with either dust continuum or NH3 peaks. For clumps G18.17, G18.21, G23.97N, and G23.98 in prestellar stages, there are very weak infrared and millimeter emissions blended with NH2D distributions. For clumps G23.44, G23.97S, and G25.38 in protostar stages, NH2D distributions are extended and surround the 3.5 mm peaks. Only for clump G25.71 (in a protostar stage) is the NH2D core located at the peak of the 3.5 mm continuum, though it is likely that the 3.5 mm continuum core is just located in the background of the NH2D core along the line of sight.

Based on temperature distributions of dense cores, we find that the suitable habitat for NH2D is 13–20 K, with deuterium fractionations reaching a maximum at 16.5 K. For temperatures higher than 20 K, NH2D activity is likely inhibited. At temperatures below 13 K, NH2D may also tend to freeze out onto dust grains. However, we should also consider that the rotational temperature tracer NH3 may be completely frozen onto dust grains before NH2D.

4.2. N-bearing Species

Some N-bearing species are widely used as good tracers of dense gas and cold conditions in initial star formation because they do not freeze out onto dust grains under these conditions (e.g., Suzuki et al. 2018; Awad & Shalabiea 2020; Peng et al. 2022). However, different N-bearing species probe slightly different physical conditions. In this work, we examine five N-bearing species: NH3 (1, 1) and (2, 2), NH2D, H13CN, and HC15N. From the integrated emissions in Figures A1–A3, A5, and A6, NH3 (1, 1) and (2, 2) are more widely distributed than others, while HC15N lines are much weaker and appear only at peak positions of these samples.

We detect almost no HC15N emission toward G18.17, G18.21, G23.97N, and G23.98, which are in relatively early star formation or prestellar stages, but we do detect HC15N emission in G23.44, G23.97S, G25.38, and G25.71, which are in protostar stages. Therefore, HC15N may trace these evolved protostars. NH2D emissions are extended but offset from continuum and NH3 peaks, allowing it to trace the earliest star-forming conditions among the five N-bearing species. H13CN emissions are distributed in an extended way and agree well with the peak positions of the 3.5 mm continuum in all samples except G23.98. Therefore, H13CN may cover a relatively extensive evolutionary process from early to evolved stages.

Li et al. (2024) also found that NH2D and H13CN have different distributions with asymmetrically and resolvably distributed spatial structures in 11 of 18 sources, while others show no significant differences. They attribute this mainly to resolution and sensitivity limitations. However, in our high-spatial-resolution and high-sensitivity observations, the emission distributions between NH2D and H13CN are strongly different, which should result from their different habitats. NH2D prefers to be located in colder conditions than H13CN.

Some key findings are as follows: The NH3 cores are in good agreement with the 3.5 mm emission peak, but NH3 is much more extended than the 3.5 mm emission structure. The NH2D cores are mainly located in the temperature range of 13.0-20.0 K, and NH2D lines may be strongly depleted above 20 K. Comparing column densities between NH2D and continuum cores, we find that NH2D distributions are in a relatively diffuse condition. In these relatively early star formation conditions, we detect almost no HC15N emission toward G18.17, G18.21, G23.97N, and G23.98, but we detect HC15N emission in G23.44, G23.97S, G25.38, and G25.71, which are in protostar stages. It is likely that HC15N traces these evolved protostars. H13CN emissions are distributed in an extended way and agree well with the peak position of the 3.5 mm continuum in all samples except G23.98. The SO distributions agree well with the 3.5 mm peaks for evolved star formation stages, except that the peak for G25.38 is offset from the 3.5 mm emission. However, we did not detect any SO emission in the four prestellar sources. We also found that at low temperatures (\$ 20*K*)*andhighdensities*(10^6\$ cm^{-3}), the C18O molecule rapidly freezes onto dust grains and becomes severely depleted. Based on these results, C18O is a poor tracer in very early star formation or prestellar cores but could be used to study diffuse (\$ 10^4\$ cm^{-3}) and warm (\$ \$20 K) star formation regions.

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Appendix

Figure Materials

Figure A1. NH3 (1, 1) integrated-intensity contours overlaid on 3.5 mm continuum emission with velocity range covering only the main line. The contour levels start at -3σ in steps of 3σ for NH3 (1, 1) with σ(a)-(h) = 12.5, 20.2, 9.1, 9.8, 15.8, 12.6, 12.9, 10.2 mJy beam^{-1} km s^{-1}. The synthesized beam size of each subfigure is indicated at the bottom-left corner.

Figure A2. NH3 (2, 2) integrated-intensity contours overlaid on 3.5 mm continuum emission with velocity range covering only the main line. The contour levels start at -3σ in steps of 3σ for NH3 (2, 2) with σ(a)-(h) = 10.8, 13.5, 7.9, 7.2, 12.3, 8.2, 9.7, 8.3 mJy beam^{-1} km s^{-1}. The synthesized beam size of each subfigure is indicated at the bottom-left corner.

Figure A3. NH2D integrated-intensity contours overlaid on 3.5 mm continuum emission with velocity range covering all six HFS lines. The contour levels start at -3σ in steps of 3σ for NH2D with σ(a)-(l) = 60.4, 60.9, 51.1, 53.2, 84.1, 48.3, 49.0, 50.4 mJy beam^{-1} km s^{-1}. The green numbers indicate the positions of extracted NH2D cores and condensations. The synthesized beam size of each subfigure is indicated at the bottom-left corner.

Figure A4. NH2D integrated-intensity contours overlaid on an NH3 integrated-intensity image with velocity range covering all six HFS lines. The contour levels start at -3σ in steps of 3σ for NH2D with σ(a)-(l) = 60.4, 60.9, 51.1, 53.2, 84.1, 48.3, 49.0, 50.4 mJy beam^{-1} km s^{-1}. The synthesized beam size of each subfigure is indicated at the bottom-left corner.

Figure A5. H13CN integrated-intensity contours overlaid on 3.5 mm continuum emission with velocity range covering all three HFS lines. The contour levels start at -3σ in steps of 3σ for H13CN with σ(a)-(l) = 63.3, 58.4, 37.6, 60.9, 97.6, 73.0, 84.8, 90.1 mJy beam^{-1} km s^{-1}. The synthesized beam size of each subfigure is indicated at the bottom-left corner.

Figure A6. HC15N integrated-intensity contours overlaid on 3.5 mm continuum emission with velocity range covering only the emission line. The contour levels start at -3σ in steps of 3σ for HC15N with σ(a)-(l) = 88.5, 69.3, 73.8, 81.8, 61.4, 58.0, 55.1, 48.3 mJy beam^{-1} km s^{-1}. The synthesized beam size of each subfigure is indicated at the bottom-left corner.

Figure A7. SO integrated-intensity contours overlaid on 3.5 mm continuum emission with velocity range covering only the emission line. The contour levels start at -3σ in steps of 3σ for SO with σ(a)-(h) = 71.4, 61.4, 52.1, 46.7 mJy beam^{-1} km s^{-1}. The synthesized beam size of each subfigure is indicated at the bottom-left corner.

Figure A8. C18O integrated-intensity contours overlaid on 3.5 mm continuum (BCD track) with velocity range covering only the emission line. The contour levels start at -3σ in steps of 3σ for C18O with σ(a)-(l) = 330.3, 151.1, 185.1, 204.7, 520.1, 214.6, 184.9, 198.8 mJy beam^{-1} km s^{-1}. The synthesized beam size of each subfigure is indicated at the bottom-left corner.

5. Summary

This work is a follow-up to Zhang et al. (2019, 2020), where we studied gas dynamics, NH2D chemistry, and fragmentation in eight massive precluster and protocluster clumps: G18.17, G18.21, G23.97N, G23.98, G23.44, G23.97S, G25.38, and G25.71. The observational data are from high spatial resolution interferometric observations with PdBI and VLA. In this work, we present spectral data including NH3, NH2D, H13CN, HC15N, SO, and C18O, and study the possible habitats for these tracers in the early stages of high-mass star formation. Our key findings are:

- NH3 cores are in good agreement with the 3.5 mm emission peak, but NH3 is much more extended than the 3.5 mm emission structure.
- NH2D cores are mainly located in the temperature range of 13.0–20.0 K, and NH2D lines may be strongly depleted above 20 K. Comparing column densities between NH2D and continuum cores, we find that NH2D distributions are in a relatively diffuse condition.
- In these relatively early star formation conditions, we detect almost no HC15N emission toward G18.17, G18.21, G23.97N, and G23.98, but we detect HC15N emission in G23.44, G23.97S, G25.38, and G25.71, which are in protostar stages. It is likely that HC15N traces these evolved protostars.
- H13CN emissions are distributed in an extended way and agree well with the peak position of the 3.5 mm continuum in all samples except G23.98.
- SO distributions agree well with the 3.5 mm peaks for evolved star formation stages, except that the peak for G25.38 is offset from the 3.5 mm emission. However, we did not detect any SO emission in the four prestellar sources.
- We also found that at low temperatures (\$ $20K)andhighdensities($ 10ˆ6\$ cm^{-3}), C18O molecules rapidly freeze onto dust grains and become severely depleted. Based on these results, C18O is a poor tracer in very early star formation or prestellar cores, but could be used to study diffuse (\$ 10ˆ4\$ cm^{-3}) and warm (\$ \$20 K) star formation regions.

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Note: Figure translations are in progress. See original paper for figures.

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