EXTERNALLY HEATED PROTOSTELLAR CORES IN THE OPHIUCHUS STAR-FORMING REGION

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ABSTRACT

We present APEX 218 GHz observations of molecular emission in a complete sample of embedded protostars in the Ophiuchus star-forming region. To study the physical properties of the cores, we calculate H2CO and c-C3H2 rotational temperatures, both of which are good tracers of the kinetic temperature of the molecular gas. We find that the H2CO temperatures range between 16 K and 124 K, with the highest H2CO temperatures toward the hot corino source IRAS 16293-2422 (69–124 K) and the sources in the ρ Oph A cloud (23–49 K) located close to the luminous Herbig Be star S1, which externally irradiates the ρ Oph A cores. On the other hand, the c-C3H2 rotational temperature is consistently low (7–17 K) in all sources. Our results indicate that the c-C3H2 emission is primarily tracing more shielded parts of the envelope whereas the H2CO emission (at the angular scale of the APEX beam; 3600 au in Ophiuchus) mainly traces the outer irradiated envelopes, apart from in IRAS 16293-2422, where the hot corino emission dominates. In some sources, a secondary velocity component is also seen, possibly tracing the molecular outflow.

Key words: astrochemistry – ISM: individual objects (Ophiuchus) – ISM: molecules – radiative transfer – stars: formation

Supporting material: machine-readable tables

1. INTRODUCTION

Low-mass protostars form from the collapse of dense molecular clouds. In their youngest stages, such protostars are deeply embedded in an envelope of dust and gas. Investigations of molecular emission lines of this envelope can be used to study both chemical and physical characteristics of the protostar. The temperature of the large-scale envelope is generally low (~10–15 K; e.g., Bergin & Tafalla 2007), but parts of the envelope can be heated by irradiation from the protostar itself or by external sources.

Molecular emission lines of H2CO with the same J=0 quantum number can be used as a probe of the kinetic temperature for cool (T \( \lesssim \) 50 K) gas at densities \( \gtrsim 10^5 \) cm\(^{-3} \) (Mangum & Wootten 1993). Through an unbiased survey of H2CO toward embedded sources in the Corona Australis (CrA) star-forming region, it was possible to characterize the temperature and external irradiation of such protostars, identifying the Herbig Be star R CrA as the dominant source of irradiation in CrA, heating nearby envelopes to temperatures \( \sim 40 \mathrm{K} \), but also influencing the temperature on scales of a few 10,000 au (Lindberg et al. 2015). The same molecular transitions were used by Lindberg & Jørgensen (2012) to produce an interferometric map of the physical characteristics in the R CrA cloud (which hosts a handful of embedded low-mass protostars). The rotational temperatures of H2CO were found to exceed 40 K across the whole cloud (~6000 au), consistent with Herschel/PACS observations of the extended dust temperature (Lindberg et al. 2014). In particular, strong H2CO and CH3OH emission with high temperatures and column densities was detected toward two long (~5000 au) ridges north and south of the low-mass young stellar objects (YSOs), whereas only faint H2CO emission was detected toward the YSOs themselves. On the other hand, most of the fainter c-C3H2 emission was detected from the region between the two ridges. The signal-to-noise ratio (S/N) of the observations was too low to establish c-C3H2 rotational temperatures, but in single-dish APEX observations the rotational temperature of c-C3H2 was found to be consistently low (~10 K) toward the embedded protostars in CrA (Lindberg et al. 2015).

The Ophiuchus star-forming region, at a distance of only 125 pc (de Geus et al. 1989; Wilking et al. 2008), is an excellent laboratory to test the knowledge gained from the CrA survey on a region with a greater number of potential heating sources, but also greater separation between the low-mass sources, allowing for a distinction between effects from internal and external heating. The population of deeply embedded protostars was surveyed by Jørgensen et al. (2008) and Enoch et al. (2009) using Spitzer and JCMT/SCUBA continuum observations, and in combination, the two surveys identified 38 Class 0 and Class I protostars. Kamegai et al. (2003) found large-scale elevated [C I] excitation temperatures in the ρ Oph A cloud using the Mount Fuji submillimeter telescope, and identified the B2 star HD 147889 as the heating source. Liseau et al. (2015), however, concluded that HD 147889 and the B4 star S1 (also known as GSS 35) both influence the temperature of the cloud, but that S1, despite being less luminous, is the more dominant heating source owing to its proximity to the ρ Oph A cloud. Here, we investigate the influence these luminous stars have on the physical properties of the molecular gas in nearby embedded protostars through 218 GHz spectral line observations.
2. OBSERVATIONS

Our observations were executed with the APEX (Atacama Pathfinder Experiment) 12 m telescope (Güsten et al. 2006) in position-switching mode in August and October 2014 and May 2015. The SHeFi APEX-1 receiver (Vassilev et al. 2008) was used to cover the frequency range 216–220 GHz toward a complete sample of the 38 deeply embedded protostellar sources in the Ophiuchus star-forming region. The sample consists of all embedded protostellar sources in the region detected by Jørgensen et al. (2008) and Enoch et al. (2009); see Table 1 and Figures 1–2. The spectral setup was chosen to cover three H$_2$CO spectral lines at 218 GHz, and also several spectral lines of c-C$_3$H$_2$, an abundant tracer of unsaturated hydrocarbon molecules.

We note that five of the sources in the sample (GSS 26, GSS 39, Elias 28, J162624, and J1633.92442) should be considered Class II sources by both the $T_{\text{mb}} > 650$ K and the $\alpha_{\text{TB}} < -0.3$ criteria (Evans et al. 2009), but are still included in the sample of embedded protostars of Jørgensen et al. (2008) due to their proximity ($<15''$) to a SCUBA core. We detect no line emission toward one of these sources (J1633.92442) and only c$^{18}$O line emission toward two (GSS 39 and Elias 28), and these sources are thus likely not deeply embedded. GSS 26 and J162624, however, show H$_2$CO line emission, indicating the presence of dense molecular gas. Finally, toward the two Class I sources WL16 and Oph-emb 4, we only detect emission from C$^{18}$O.

To remove quasi-sinusoidal baselines present in the APEX-1 spectra (see Vassilev et al. 2008), we used our running-mean script described in Appendix A of Lindberg et al. (2015). The spectra were thereafter reduced with the X-Spec package, which was used to average scans, perform Gaussian fits, and calculate line intensities. Throughout the paper we use the $T_{\text{mb}}$ temperature scale, assuming a main beam efficiency $\eta_{\text{mb}} = 0.75$.

3. SPECTRAL LINE PROFILES

The spectral lines that were used in the analysis are listed in Table 2. These lines were not detected toward all sources, and in addition to these lines, several other lines (of e.g., C$_2$D, DCN, C$^{18}$O, C$_3^{33}$S, and HNCO) were detected in some of the sources, but will not be discussed in this paper. All observed line parameters are listed in Table 4 in Appendix A.

To enable comparison of the line profiles, Figure 3 shows the normalized spectra for the strongest DCO$^+$ (216.113 GHz), c-C$_3$H$_2$ (217.822 GHz), H$_2$CO (218.222 GHz), and SO (219.949 GHz) lines in each source where they have been detected. We note that for some sources, the line profiles of different molecular species are dramatically discrepant. In several cases, a double peak is seen in some spectral lines. The CH$_3$OH line (not plotted) is generally well-correlated with the H$_2$CO line shape, while C$_2$D (not plotted) correlates well with c-C$_3$H$_2$, although the C$_2$D line doublet makes analysis of the line profile non-trivial. Of the plotted lines, we find that the line profiles often separate the molecular species into two groups: H$_2$CO and SO on one hand, and c-C$_3$H$_2$ and DCO$^+$ on the other. Lindberg et al. (2015) found that H$_2$CO and other saturated organic species as well as SO and other sulfur-bearing species had significantly higher rotational temperatures than c-C$_3$H$_2$ and other unsaturated hydrocarbons in the APEX observations of the embedded protostar R CrA IR$S7B$. As in CrA, the H$_2$CO and SO line profiles are generally wider than the c-C$_3$H$_2$ line profiles. This is also similar to the six molecular cores studied by Buckle et al. (2006), where CH$_3$OH and SO were found to be spatially correlated, but separated from the unsaturated hydrocarbon HC$_3$N.

For completeness, the corresponding spectra for the Corona Australis region are shown in Figure 8 of Appendix B.

3.1. Secondary Components

In at least nine sources (four in $\rho$ Oph A, three in $\rho$ Oph B, one in L1689S, and IRAS 16293-2422), a secondary component to some of the emission lines is detected. This was also seen in two sources in the CrA survey: SMM2 and CrA-24. In all 11 cases, the additional component is characterized by strong H$_2$CO and CH$_3$OH emission, and often also SO, but faint or no emission from other species. In CrA, the component likely comes from an overlapping molecular outflow (O. Miettinen et al. 2016, in preparation). We note that the velocity of the secondary component is blueward of the main component in five out of seven $\rho$ Oph A and $\rho$ Oph B sources, with the exceptions ISO-Oph 21 and J162614.6.

To account for the possibly distinct nature of these secondary velocity components, they are treated separately from the main component in the rotational temperature analysis, and are plotted as red data points in all plots (although they are typically not the redward components). We identify which component is to be considered “secondary” by investigating the molecular emission prevalent at those velocities—typically, the secondary component has little or no DCO$^+$ and c-C$_3$H$_2$ emission. The secondary component is often also wider than the main component, and usually appears at a velocity different from the typical velocity of other sources in the same cloud (thus possibly representing a molecular outflow). For the rotational diagram analysis (see below), emission from the two components were separated by performing Gaussian fits. We find that the secondary component in most cases has a higher H$_2$CO rotational temperature than the main component, in agreement with the CrA sources.

4. ROTATIONAL TEMPERATURES

For all sources where at least two H$_2$CO or c-C$_3$H$_2$ spectral lines were detected, the respective rotational temperatures (assuming LTE) have been calculated. We assume that the lines are optically thin, which is valid at the observed column densities (Lindberg et al. 2015). For sources with only one detected line of a certain species, an upper limit of the rotational temperature was calculated using the upper limits on the non-detected line(s). The results are presented in Table 3.

The three observed H$_2$CO lines all have the same $J_a = 3$, and their rotational temperature is thus an excellent proxy for the kinetic temperature, but makes estimates of the column density more uncertain (Mangum & Wootten 1993; Lindberg et al. 2015). We estimate the beam-averaged H$_2$CO column densities using the non-LTE radiative transfer code RAXED (van der Tak et al. 2007) assuming an H$_2$ number density of $(8.9 \pm 1.0) \times 10^5$ cm$^{-3}$ in all sources. This value was measured from observations of multiple H$_2$CO $J_a = 3$ and $J_a = 5$ lines toward the protostar R CrA IR$S7B$ at a similar...
beam size using non-LTE methods (RADEX), and is of the same order of magnitude as found in the protostars in CrA where this value could be measured (Lindberg et al. 2015). All observed H$_2$CO lines are para lines, and an ortho-to-para ratio is therefore not important for the excitation analysis. However, such a ratio is necessary to calculate the total H$_2$CO column density, and for this purpose an ortho/para ratio of 1.6 is assumed (see Lucas & Liszt 2000). Non-LTE RADEX models of c-C$_3$H$_2$ show that its physical temperature is well-represented by the rotational temperature if $n$(H$_2$) $> 10^5$ cm$^{-3}$, at temperatures typical for protostellar envelopes. This is further discussed in Appendix C (see also Spezzano et al. 2016).

The H$_2$CO rotational temperatures in the Ophiuchus star-forming region are generally higher than what is expected in low-mass protostars on the scale of the APEX primary beam
Internal heating by low-mass embedded protostars would produce temperatures \( \sim 10^{15} \) K on these scales (Bergin & Tafalla 2007). The \( \text{H}_2\text{CO} \) temperatures observed toward most sources thus require an external radiation field to be explained (see e.g., Jørgensen et al. 2006; Lindberg & Jørgensen 2012).

4.1. IRAS 16293-2422

The highest \( \text{H}_2\text{CO} \) rotational temperature in the survey was measured toward the Class 0 protostar IRAS 16293-2422 (69 \( \pm \) 1 K in the main component and 124 \( \pm \) 4 K in the secondary component). This source is the best-studied example of a hot corino (see, e.g., Cazaux et al. 2003; Caux et al. 2011), and as shown by interferometric observations, most of the line emission from organic species originates in the hot inner envelope (\( R \lesssim 100 \) au), where the central object heats the molecular gas to high temperatures (e.g., Bisschop et al. 2008).

In contrast to the other sources in the survey (see below), which are not known to exhibit hot corino properties, the \( \text{H}_2\text{CO} \) temperature measured toward IRAS 16293-2422 likely traces the properties of this hot and dense inner envelope. Most other sources in the sample are also at a later stage of evolution than...
IRAS 16293-2422 as shown by their higher bolometric temperature.

However, the c-C₃H₂ temperatures measured toward IRAS 16293-2422 are much lower, only 14.4 ± 0.3 K and 16.5 ± 1.5 K for the main and secondary components, respectively, marginally higher than the values found in the other sources in the survey, thus likely tracing emission on larger scales.

4.2. External Heating of Sources in ρ Oph A and ρ Oph B

The H₂CO rotational temperatures are somewhat higher toward the sources in the ρ Oph A cloud than in the ρ Oph B cloud. With
| Cloud Source | $T_{\text{rot}}$ (K) | $N$ ($10^{12}$ cm$^{-2}$) | $\Delta V$ (km s$^{-1}$) | $\delta_{\text{LSR}}$ (km s$^{-1}$) | $T_{\text{rot}}$ (K) | $N_{\text{rot}}$ ($10^{13}$ cm$^{-2}$) | $\Delta V$ (km s$^{-1}$) | $\delta_{\text{LSR}}$ (km s$^{-1}$) |
|--------------|---------------------|---------------------------|--------------------------|--------------------------|---------------------|-------------------------------|--------------------------|--------------------------|
| GDS J162625.6 (main) | 25.8 ± 1.0 | 18 ± 3 | 0.8 | 3.8 | 12.4 ± 0.8 | 2.5 ± 0.4 | 0.8 | 3.8 |
| GDS J162625.6 (sec.) | 36.7 ± 2.1 | 11 ± 1 | 1.4 | 2.6 | ... | ... | ... | ... |
| GSS 26 | 39.9 ± 8.7 | 4.3 ± 1.4 | 1.1 | 3.4 | ... | ... | ... | ... |
| GSS 30 | 35.4 ± 1.2 | 19 ± 2 | 1.3 | 3.3 | 14.7 ± 3.7 | 0.46 ± 0.26 | 0.9 | 3.5 |
| GSS 39 | ... | ... | ... | ... | ... | ... | ... | ... |
| [GJ92] 30 | 36.2 ± 0.4 | 79 ± 8 | 1.2 | 3.4 | 9.9 ± 0.3 | 4.0 ± 0.3 | 0.4 | 3.4 |
| [GJ92] 91 | 26.7 ± 2.0 | 12 ± 2 | 0.6 | 3.2 | ... | ... | ... | ... |
| ISO-Oph 21 (main) | 23.2 ± 1.2 | 15 ± 3 | 0.9 | 2.8 | ... | ... | ... | ... |
| ISO-Oph 21 (sec.) | 48.0 ± 4.7 | 4.4 ± 0.6 | 1.2 | 3.9 | ... | ... | ... | ... |
| J162614.6 (main) | 29.0 ± 0.5 | 47 ± 6 | 0.9 | 2.7 | ... | ... | ... | ... |
| J162614.6 (sec.) | 49.2 ± 2.2 | 11 ± 1 | 1.5 | 4.3 | ... | ... | ... | ... |
| VLA 1623 (main) | 30.6 ± 1.0 | 23 ± 3 | 0.8 | 3.8 | 11.2 ± 0.5 | 4.2 ± 0.5 | 0.8 | 3.8 |
| VLA 1623 (sec.) | 28.3 ± 2.1 | 12 ± 2 | 1.4 | 2.5 | ... | ... | ... | ... |
| GDS J162625.6 (main) | 17.0 ± 1.2 | 23 ± 5 | 1.1 | 4.3 | ... | ... | ... | ... |
| GDS J162625.6 (sec.) | 19.1 ± 1.7 | 9.2 ± 2.4 | 0.5 | 3.1 | ... | ... | ... | ... |
| J162728 (main) | 20.0 ± 1.1 | 21 ± 4 | 0.6 | 4.2 | 10.2 ± 0.2 | 4.1 ± 0.3 | 0.4 | 4.3 |
| J162728 (sec.) | 16.2 ± 1.5 | 13 ± 4 | 0.5 | 3.4 | 6.9 ± 0.5 | 1.9 ± 0.5 | 0.5 | 3.7 |
| Oph-emb 5 | 15.5 ± 0.7 | 55 ± 12 | 0.8 | 3.7 | 8.7 ± 1.0 | 1.0 ± 0.4 | 0.5 | 3.9 |
| VSSG 17 (main) | 23.7 ± 1.8 | 12 ± 2 | 0.8 | 4.4 | 10.9 ± 0.4 | 3.2 ± 0.4 | 0.5 | 4.3 |
| VSSG 17 (sec.) | 18.7 ± 2.9 | 6.2 ± 2.4 | 0.5 | 3.3 | ... | ... | ... | ... |
| [GJ92] 197 | <61.6 | ... | 0.9 | 4.8 | ... | ... | ... | ... |
| WL 15 | <109 | ... | 2.2 | 4.5 | ... | ... | ... | ... |
| WL 16 | ... | ... | ... | ... | ... | ... | ... | ... |
| WL 19 | <292 | ... | 0.9 | 4.6 | ... | ... | ... | ... |
| IRAS 16244-2432 | <66.6 | ... | 1.9 | 3.7 | ... | ... | ... | ... |
| IRAS 16246-2436 | <28.5 | ... | 0.6 | 3.7 | <7.5 | ... | 0.3 | 3.7 |
| ISO-Oph 132 | <138 | ... | 0.3 | 4.0 | ... | ... | ... | ... |
| ISO-Oph 137 | <34.3 | ... | 1.3 | 4.4 | 6.7 ± 0.8 | 2.5 ± 1.0 | 0.2 | 4.0 |
| ISO-Oph 161 | <43.6 | ... | 0.6 | 3.8 | <7.9 | ... | 0.4 | 3.7 |
| VLYW 15 | <35.4 | ... | 2.4 | 3.9 | 7.8 ± 0.7 | 2.6 ± 0.8 | 0.4 | 4.1 |
| IRAS 16293-2422 (main) | 69.4 ± 0.9 | 47 ± 3 | 2.7 | 4.8 | 14.4 ± 0.3 | 6.5 ± 0.3 | 1.3 | 4.6 |
| IRAS 16293-2422 (sec.) | 124 ± 3 | 32 ± 1 | 1.7 | 3.2 | 16.5 ± 1.5 | 2.4 ± 0.5 | 1.7 | 3.1 |
| ISO-Oph 200 | <35.2 | ... | 0.8 | 4.7 | ... | ... | ... | ... |
| ISO-Oph 202 | <46.4 | ... | 0.8 | 4.6 | ... | ... | ... | ... |
| ISO-Oph 203 (main) | 23.4 ± 1.9 | 5.9 ± 1.2 | 0.5 | 4.5 | 9.3 ± 0.4 | 1.9 ± 0.3 | 0.4 | 4.4 |
| ISO-Oph 203 (sec.) | 22.3 ± 2.7 | 4.0 ± 1.1 | 0.4 | 4.9 | ... | ... | ... | ... |
| ISO-Oph 209 | <62.3 | ... | 1.3 | 4.2 | ... | ... | 1.3 | 2.9 |
| GWAYL 4 | <54.7 | ... | 0.5 | 2.8 | ... | ... | 1.3 | 3.0 |
| Oph-emb 4 | ... | ... | ... | ... | ... | ... | ... | ... |
| Solitary sources | Elias 28 | ... | ... | ... | ... | ... | ... | ... |
| J162624 | <68.6 | ... | 0.8 | 3.3 | ... | ... | ... | ... |
| J1633.9244 | ... | ... | ... | ... | ... | ... | ... | ... |
| MMS126 | <22.4 | ... | 0.4 | 4.1 | 8.6 ± 0.3 | 4.4 ± 0.5 | 0.4 | 4.1 |
| Oph-emb 18 | ... | ... | 0.2 | 3.5 | ... | ... | ... | ... |

Note. The H$_2$CO column densities were calculated by non-LTE methods assuming $n$(H$_3$) = ($8.9 \pm 1.0$) $\times$ 10$^5$ cm$^{-3}$ (see Section 4). The line widths and LSR velocities are median values. Section 3.1 describes the main and secondary components.

(This table is available in machine-readable form.)
two exceptions (IRAS 16293-2422 and ISO-Oph 203), all of the sources where the H$_2$CO temperatures could be measured are located in these two clouds, and it is therefore not possible to judge whether the H$_2$CO temperatures of these clouds are representative of protostellar envelopes in the whole region.

The luminous Herbig Be star S1 is located only 2$''$ (∼15 000 au) east of ρ Oph A. It has spectral class B4 (Bouvier & Appenzeller 1992) and luminosity ∼1000–1600L_{⊙} (Bontemps et al. 2001; Wilking et al. 2005). About 15$''$ (0.5 pc) west of the cloud lies the even more luminous B2 star HD 147889 (Houk & Smith-Moore 1988), with a luminosity ∼4500L_{⊙} (Greene & Young 1989). In their radiative transfer models, Liseau et al. (2015) use the luminosities of S1 and HD 147889 of 1100L_{⊙} and 4500L_{⊙}, respectively.

In Figure 4, the rotational temperatures of H$_2$CO and c-C$_3$H$_2$ are plotted as a function of the projected distance to S1. We also calculate how the luminous source S1 influences the dust temperature, and thus indirectly the molecular gas temperature, using a 1D Transphere model (Dullemond et al. 2002). We assume the luminosity of S1 to be 1600L_{⊙} and a constant cloud density n(H$_2$) = $10^4$ cm$^{-3}$. The model (dashed line in Figure 4) underpredicts the observed H$_2$CO temperatures of the sources in ρ Oph A and ρ Oph B somewhat, but the irradiation from HD 147889 and the internal irradiation from the embedded sources are not included in the model, which could account for the difference. A density different from our assumption, or a non-uniform density distribution within the cloud, could also play a role in explaining the discrepancy.

To compare the contribution from the two heating sources, and to find the dominant source of heating in any given part of the cloud, Figure 5 shows where the heating from both sources are equal (black contour). This plot was made with two important assumptions limiting the level of interpretations to be made, namely that the cloud is uniformly dense (n(H$_2$) = $10^4$ cm$^{-3}$) and that all sources lie in the same plane of sky.

### 4.3. Temperatures of H$_2$CO and c-C$_3$H$_2$

The H$_2$CO rotational temperature in the protostellar envelopes is strongly enhanced in the sources located close to the Herbig Be star S1 and the very luminous star HD 147889, whereas the c-C$_3$H$_2$ rotational temperature is around 10–15 K in all sources (similar to the rotational temperatures of unsaturated hydrocarbon species observed in so-called warm carbon-chain chemistry sources, a type of deeply embedded protostar with high abundances of unsaturated carbon-chain molecules; see, e.g., Sakai & Yamamoto 2013). The same trend is found in a similar study in the CrA star-forming region (Lindberg et al. 2015). For some reason, the H$_2$CO gas is more prone to be heated by external radiation fields, or the H$_2$CO abundance is enhanced in the irradiated gas, possibly due to photochemistry (see, e.g., Guzmán et al. 2011). We propose that the H$_2$CO emission originates in relatively outer regions of the envelope (on scales of R ∼ 2000 au; toward the edge of the APEX beam) more exposed to the external irradiation field, while the c-C$_3$H$_2$ emission originates in inner regions of the envelope, where it is shielded against the external irradiation. This is consistent with interferometric observations of the externally irradiated protostar R CrA IRS7B, which show heated H$_2$CO in large structures a few 1000 au from the central low-mass objects, while the c-C$_3$H$_2$ is found closer to the protostars (Lindberg & Jørgensen 2012).
Surprisingly, the same differentiation in temperature between H₂CO and c-C₃H₂ is found toward IRAS 16293-2422, where the high H₂CO temperature must have an internal origin (see above). The c-C₃H₂ gas likely also exists in this hot inner envelope, but the bulk of the emission possibly traces an intermediately deep region of the protostellar envelope, too deeply embedded to be heated by external irradiation, but also far from the internal heating source that gives rise to the hot corino chemistry of the inner 50–100 au of IRAS 16293-2422, where the temperature is >100 K, making complex organic molecules as well as H₂CO evaporate from the icy grain mantles.

5. CORRELATIONS BETWEEN DIFFERENT SPECIES

In this section, to evaluate the statistical significance of any correlations, we use Spearman’s ρ rank correlation test, which tests the monotonicity of two sets of variables without requiring a linear relation or a normal distribution of the variables. The H₂CO and c-C₃H₂ rotational temperatures and column densities are given in Table 3. The CH₃OH column densities were estimated using the CH₃OH line at 218.440 GHz and the H₂CO rotational temperature as a proxy for the CH₃OH rotational temperature. This assumption is based on the similar origin of these two molecules (hydrogenation of CO on grain mantles; see, e.g., Charnley 1997), interferometric observations showing them to be spatially co-aligned in protostellar envelopes (e.g., Lindberg & Jørgensen 2012), and the similar critical densities of the observed H₂CO and CH₃OH lines (a few × 10⁵ cm⁻³; Guzmán et al. 2011, 2013). We used RADEX models to find that the CH₃OH line at 218.440 GHz is optically thin and that our method provides reliable values on the CH₃OH column density assuming n ∼ 10⁶ cm⁻³ and T ≤ 40 K (see also Lindberg et al. 2016).

Lindberg et al. (2015) suggested a trend between the H₂CO rotational temperature and the CH₃OH/H₂CO ratio in the embedded protostars of CrA. In Figure 6 we plot the CH₃OH/H₂CO column density ratio as a function of the H₂CO rotational temperature, and find that they have a strong correlation (Spearman’s rank test gives ρ = 0.62 with p < 0.001). If the data points of the hot corino source IRAS 16293-2422 are disregarded (since the bulk of this emission should originate in the hot inner envelope), the correlation weakens somewhat (ρ = 0.52 with p < 0.01). However, if the secondary components are also disregarded due to their uncertain origin, there is no significant correlation between the CH₃OH/H₂CO and the H₂CO rotational temperature. A correlation would be in agreement with laboratory results that, suggest that the grain-surface hydrogenation reactions forming CH₃OH are more efficient at higher temperatures (e.g., Fuchs et al. 2009). The exact mechanism behind CH₃OH evaporation at low temperatures, however, remains unclear (Bertin et al. 2016; Martín-Domènech et al. 2016).

In Figure 7, we investigate the correlation between the rotational temperatures and column densities of H₂CO, CH₃OH, and c-C₃H₂. The CH₃OH column density was estimated assuming Tₗ=CH₃OH = Tₗ=H₂CO. We find no correlation between the H₂CO rotational temperature and column density (ρ = 0.14, p ≈ 0.44), but the CH₃OH column density is moderately correlated with the H₂CO temperature (ρ = 0.58, p ≈ 0.001), which indicates that CH₃OH production is enhanced by high temperatures or radiation fields (grain-mantle evaporation and/or enhancement of hydrogenation reactions on grain surfaces; cf. Öberg et al. 2009). If the hot corino source IRAS 16293-2422 is disregarded, the correlation is still significant (ρ = 0.48, p < 0.02). For c-C₃H₂ there is no significant correlation between its rotational temperature and column density (not plotted; ρ = 0.19, p ≈ 0.41), which would suggest that its formation is not temperature dependent. We find a very strong correlation between the H₂CO and CH₃OH column densities (ρ = 0.82, p < 10⁻⁶), indicating that these molecules share a common origin (e.g., grain-mantle hydrogenation of CO). To exclude the possibility of this correlation being biased by the fact that we use the H₂CO temperature to find the CH₃OH column density, we also performed this calculation assuming a fixed Tₗ=CH₃OH = 10 K for all sources, and still find a strong correlation between N(H₂CO) and N(CH₃OH). Finally, the c-C₃H₂ and H₂CO column densities show a barely significant correlation (ρ = 0.52, p ≈ 0.04).

6. SUMMARY AND CONCLUSIONS

We find that the H₂CO temperature in protostellar cores depends strongly on the distance to external sources of strong irradiation, whereas the c-C₃H₂ temperature is insensitive to such irradiation (see Figure 4). This implies that the H₂CO traces the outer, externally irradiated layers of the protostellar cores, whereas the emission from c-C₃H₂ originates primarily in the inner, more shielded region. However, in the hot corino source IRAS 16293-2422, the majority of the c-C₃H₂ gas appears to mainly trace an intermediate region, shielded from any external irradiation, but sufficiently distant from the central protostar to remain relatively cool.

We also find that the column densities of the two molecules H₂CO and CH₃OH are closely related, suggesting that they share a common origin. Interferometric observations would be necessary to confirm that they spatially co-exist, and also to study the nature of the secondary components found toward many of the studied sources.

The chemical implications of external heating are still not well understood. A comparative study using interferometric observations of similar protostars within the same star-forming region but with different levels of external irradiation could be used to investigate the origin of the differences in chemical composition and distribution. We suggest future line surveys searching for complex organic molecules and hydrocarbon species, and interferometric mapping of a few key species in the most luminous sources of ρ Oph A and ρ Oph B.
Figure 7. Plots studying trends between rotational temperatures and column densities of H$_2$CO, CH$_3$OH, and c-C$_3$H$_2$. The CH$_3$OH column density was estimated assuming $N$(CH$_3$OH) = $T_{\text{rot}}$(H$_2$CO). The semi-transparent data points represent similar embedded sources in the CrA star-forming region (Lindberg et al. 2015). Red data points represent the secondary component dominated by H$_2$CO, CH$_3$OH, and SO in sources with two line components (see Section 3.1).

Table 4: Measured Line Parameters

| Source            | Molecule | Transition | $v_{\text{LSR}}$ (km s$^{-1}$) | $\Delta v$ (km s$^{-1}$) | $\int T_{\text{mb}} dv$ (K km s$^{-1}$) |
|-------------------|----------|------------|-------------------------------|--------------------------|---------------------------------|
| Rest freq. (MHz)  |          |            |                               |                          |                                 |
| GDS J162625.6 (main) |          |            |                               |                          |                                 |
| 216112.58         | DCO$^+$  | $J = 3$–$2$ | 3.8                           | 0.8                      | 3.84 ± 0.03                     |
| 216278.76         | c-C$_3$H$_2$ | $3_{00}$$^-$–$2_{21}$ | 3.8 | 0.8 | 0.28 ± 0.02 |
| 216373.32         | C$_2$D   | $N = 3$–$2, J = 7/2$–$5/2$ | 4.0 | 1.3 | 0.48 ± 0.03 |
| 216428.32         | C$_2$D   | $N = 3$–$2, J = 5/2$–$3/2$ | 3.6 | 1.0 | 0.28 ± 0.02 |
| 217258.54         | DCN      | $J = 3$–$2$ | 3.8 | 1.1 | 0.58 ± 0.03 |
| 217822.15         | c-C$_3$H$_2$ | $6_{60}$$^-$–$5_{65}$ | 3.8 | 0.8 | 0.38 ± 0.03 |
| 217940.05         | c-C$_3$H$_2$ | $5_{14}$$^-$–$4_{23}$ | 3.8 | 0.7 | 0.22 ± 0.02 |
| 218160.46         | c-C$_3$H$_2$ | $5_{24}$$^-$–$4_{13}$ | 3.9 | 1.3 | 0.09 ± 0.02 |
| 218222.19         | H$_2$CO  | $3_{00}$$^-$–$2_{02}$ | 3.9 | 0.8 | 1.87 ± 0.02 |
| 218475.63         | H$_2$CO  | $3_{22}$–$2_{21}$ | 3.8 | 0.7 | 0.17 ± 0.02 |
| 218760.07         | H$_2$CO  | $3_{21}$–$2_{20}$ | 3.8 | 0.9 | 0.16 ± 0.02 |
| 219560.35         | C$^{18}$O | $J = 2$–$1$ | 3.9 | 0.8 | 10.65 ± 0.02 |
| 219949.44         | SO       | $6_{30}$$^-$–$5_{4}$ | 4.0 | 0.7 | 1.45 ± 0.02 |

Notes. Rest frequencies from the CDMS (Müller et al. 2001) and JPL (Pickett et al. 1998) molecular spectroscopy databases. A portion is shown here for guidance regarding its form and content.

a Blend of $F = 9/2$–$7/2, F = 7/2$–$5/2$, and $F = 5/2$–$3/2$.
b Blend of $F = 7/2$–$5/2, F = 5/2$–$3/2$, and $F = 3/2$–$1/2$.
c Blend of $F = 13/2$–$11/2$ and $F = 15/2$–$13/2$.
d $F_1 = 2$–$2, F = 2$–$1$.
e $F_1 = 2$–$1, F = 2$–$1$.
f $F_1 = 2$–$1, F = 3$–$2$.
g $F_1 = 3$–$2, F = 2$–$1$.

(This table is available in its entirety in machine-readable form.)
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APPENDIX A
OBSERVED LINE PARAMETERS

Table 4 lists the detected lines in all of the observed sources. The errors on integrated intensities are 1.0 or rms errors. In a few of the sources, we found that considerable C^{18}O emission in the off position made the C^{18}O line data unreliable for those sources. Those are indicated by “Off-em.” in their integrated intensity column. We do not expect any of the other lines, which are much fainter (in particular in the diffuse gas where the off positions were measured), to be affected by off-position emission.

In sources with two components, these are listed as separate sources. LSR velocities and line widths are from Gaussian fits. In all of the other sources, they are integrated over the whole spectral line.

APPENDIX B
SPECTRAL LINE PROFILES IN CORONA AUSTRALIS SOURCES

For completeness, Figure 8 shows the spectral profiles of the sources in the CrA survey of embedded protostars (Lindberg et al. 2015) by plotting the normalized spectra for the strongest DCO^+ (216.113 GHz), c-C_3H_2 (217.822 GHz), H_2CO (218.222 GHz), and SO (219.949 GHz) lines in each source where they have been detected (cf. Figure 3).

APPENDIX C
NON-LTE ANALYSIS OF c-C_3H_2

In our observations, the rotational temperatures of c-C_3H_2 were generally found to be lower than those of H_2CO. To verify that this reflects a difference in physical temperatures and is not just a non-LTE or optical depth effect, we used the radiative transfer code RADEX (van der Tak et al. 2007) to study line ratios within a range of physical parameters. A similar investigation of the H_2CO rotational temperature was performed by Mangum & Wootten (1993), showing that a rotational temperature calculated from H_2CO transitions with the same J will provide a good measure of the physical temperature.

We here use RADEX to calculate non-LTE line ratios of four of the five c-C_3H_2 lines covered in our observations (see Table 2; the 218.733 GHz line is not included since it is only detected toward one source). One of these lines is a blend between an ortho and a para line, two lines are ortho lines, and the final one is a para line. Excitation analysis involving a combination of ortho and para lines will therefore depend on the assumed ortho-to-para ratio. For c-C_3H_2 we use a ratio of 3 (Lucas & Liszt 2000). We use the collisional rates of Chandra & Kegel (2000) retrieved from the LAMDA database (Schöier et al. 2005).

Since three of the four lines have roughly the same upper level energy (E_u = 35–39 K), we only show ratios between the 216.279 GHz line (E_u = 19.5 K) and the three remaining lines. We perform the non-LTE calculations assuming three different column densities (total ortho-para c-C_3H_2 column densities): N = 10^{12} cm^{-2}, N = 10^{13} cm^{-2}, and N = 10^{14} cm^{-2}. Our observations show that the c-C_3H_2 column densities typically are <10^{13} cm^{-2}, so the N = 10^{14} cm^{-2} case is unlikely to be applicable to this work. A model with N = 10^{11} cm^{-2} (not plotted) has results identical to the N = 10^{12} cm^{-2} model. The results are shown in Figure 9.
Figure 9. c-C$_3$H$_2$ line ratios assuming LTE (dashed lines) and with non-LTE RADEX models (solid lines).
We find that the 216.279 GHz/217.822 GHz non-LTE line ratio is within ~5 K of the LTE solution given $T_{\text{kin}} \lesssim 20$ K for all densities and column densities. The other two ratios are worse off in predicting the temperature, in particular for low H$_2$ densities. At $T_{\text{kin}} \lesssim 20$ K and $n$(H$_2$) $\gtrsim 5 \times 10^5$ cm$^{-3}$, the temperature is, however, only underpredicted (or overpredicted) by $\lesssim$5 K. Densities are expected to exceed $5 \times 10^5$ cm$^{-3}$ within the inner 1800 au of a majority of embedded protostars (e.g., Jørgensen et al. 2002), which is the radius of the APEX beam projected to the distance of the Ophiuchus cloud (125 pc).

We compare the rotational (LTE) temperatures calculated when using only the 216.279 GHz and the 217.822 GHz lines with those calculated from using all of the detected lines for all sources in the sample, and find that in no source is the difference greater than 2 K. The rotational temperatures of c-C$_3$H$_2$ presented in Table 3 use all observed c-C$_3$H$_2$ lines and might thus be underestimated, but calculating rotational temperatures from RADEX intensities shows that this difference is $\lesssim$5 K. We therefore conclude that the physical temperature of the c-C$_3$H$_2$ gas is significantly lower than that of the H$_2$CO gas in the externally irradiated sources in the sample.

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