THE COMPARISON OF PHYSICAL PROPERTIES DERIVED FROM GAS AND DUST IN A MASSIVE STAR-FORMING REGION

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ABSTRACT

We explore the relationship between gas and dust in a massive star-forming region by comparing the physical properties derived from each. We compare the temperatures and column densities in a massive star-forming Infrared Dark Cloud (G32.02+0.05), which shows a range of evolutionary states, from quiescent to active. The gas properties were derived using radiative transfer modeling of the (1,1), (2,2), and (4,4) transitions of NH3 on the Karl G. Jansky Very Large Array, while the dust temperatures and column densities were calculated using cirrus-subtracted, modified blackbody fits to Herschel data. We compare the derived column densities to calculate an NH3 abundance, \( \chi_{\text{NH}_3} = 4.6 \times 10^{-8} \). In the coldest star-forming region, we find that the measured dust temperatures are lower than the measured gas temperatures (mean and standard deviations \( T_{\text{dust,avg}} \sim 11.6 \pm 0.2 \) K versus \( T_{\text{gas,avg}} \sim 15.2 \pm 1.5 \) K), which may indicate that the gas and dust are not well-coupled in the youngest regions (~0.5 Myr) or that these observations probe a regime where the dust and/or gas temperature measurements are unreliable. Finally, we calculate millimeter fluxes based on the temperatures and column densities derived from NH3, which suggest that millimeter dust continuum observations of massive star-forming regions, such as the Bolocam Galactic Plane Survey or ATLASGAL, can probe hot cores, cold cores, and the dense gas lanes from which they form, and are generally not dominated by the hottest core.

Key words: dust, extinction – evolution – ISM: abundances – ISM: molecules – stars: formation

Online-only material: color figures

1. INTRODUCTION

Toward massive star- and cluster-forming regions, we are interested in probing the physical conditions of dense molecular gas clumps, which are highly embedded (A_V ~ 10–100). Hence, we observe at long wavelengths (\( \lambda > 70 \) \( \mu \)m), where the thermal dust emission blackbody spectrum peaks and low-energy molecular transitions can be observed. Understanding the physical conditions, such as temperature and column density, at the onset of massive star formation provides crucial constraints for models of star and cluster formation.

While a variety of molecular gas species (e.g., CO, NH3, H2CO) can be used to trace physical conditions in these dense molecular clumps, NH3 has the advantage of closely spaced inversion transitions, allowing for observations of multiple transitions in the same observing band, making it a commonly observed species (e.g., Ho & Townes 1983; Mangum et al. 1992; Longmore et al. 2007; Pillai et al. 2006, 2011). NH3 has been shown to be a reliable tracer of the mass-averaged gas temperatures to within better than 1 K (Juvela et al. 2012). The rotational energy states of NH3 are described by quintuplet numbers (J, K) and dipole transitions between different K ladders are forbidden. Therefore, their relative populations depend only on collisions and are direct probes of the kinetic temperature of the emitting gas. Each (J, K) rotational energy level is divided into inversion doublets, the (1,1) and (2,2) inversion transitions being most commonly observed (e.g., Ragan et al. 2011; Pillai et al. 2006). The hyperfine structure of the inversion transitions allows for straightforward measurements of the optical depth of the lines. The inversion doublet transitions of NH3 provide a robust tool for measuring gas temperatures and column densities.

The optically thin thermal emission from dust grains at long wavelengths can also be utilized to derive the physical conditions deep within massive star- and cluster-forming regions. In order to derive the temperature and column density of the observed dust, we fit a modified blackbody to the dust emission spectra over a range of wavelengths. The measured modified blackbody directly traces the thermal emission from dust grains and provides an estimate of the dust temperature and column density, the accuracy of which depends on the number of data points, their uncertainty, and, of course, how well the region can be approximated by the model of a modified blackbody at a single temperature, column density, and dust spectral index.

Gas and dust temperatures and column densities are generally used interchangeably in these dense molecular gas clumps. In the densest regions of these clumps we expect the gas and dust to be tightly coupled at about n > 10^{4.5} cm^{-3} (Goldsmith 2001). We note, however, that Young et al. (2004) found a higher gas-dust energy transfer rate, which may change the derived density threshold of Goldsmith (2001) by a few tens of percent. In this work, we compare the physical properties derived from gas and dust in a massive star-forming Infrared Dark Cloud (IRDC, G32.02+0.05) that shows a range of evolutionary states (Battersby et al. 2014). The gas physical properties are derived using radiative transfer modeling of three inversion transitions of para-NH3 ((1,1), (2,2), and (4,4)) observed with the Karl G. Jansky Very Large Array (VLA) by Battersby et al. (2014). The dust physical properties are derived using cirrus-subtracted modified blackbody fits data from the Herschel Infrared Galactic...
Plane Survey (Hi-GAL; Molinari et al. 2010) using the method described in Battersby et al. (2011). The column densities derived from each tracer are compared with column densities derived using 1.1 mm dust emission data from the Bolocam Galactic Plane Survey (BGPS; Ginsburg et al. 2013; Aguirre et al. 2011; Rosolowsky et al. 2010), 8 μm dust absorption data from the Galactic Legacy Mid-Plane Survey Extraordinaire (GLIMPSE; Benjamin et al. 2003) using the method from Battersby et al. (2010), and 13CO emission data from the Boston University-Five College Radio Astronomy Observatory Galactic Ring Survey (BU-FCRAO GRS or just GRS; Jackson et al. 2006).

In Section 2, we summarize the data and methods used to derive physical properties. In Section 3, we calculate the abundance of NH3 in this IRDC and compare the column densities derived from each tracer of the molecular gas. Section 4 presents a comparison of the properties derived from gas with those derived from dust. We compare the high-resolution NH3 observations with lower-resolution observation from the Green Bank Telescope (GBT) in Section 5. Finally, in Section 6, we forward model the high-resolution gas temperatures and column densities derived from the VLA to derive the millimeter fluxes that would be observed with the BGPS, allowing us to explore the high-resolution (~0.1 pc) nature of pc-scale dense, molecular clumps. We conclude in Section 7.

2. DATA

2.1. VLA NH3

The observations and radiative transfer modeling used to derive NH3 gas temperatures and column densities are presented and explained in detail in Battersby et al. (2014).

The (1,1), (2,2), and (4,4) inversion transitions of para-NH3 were observed toward two clumps within IRDC G32.02+0.06 with the National Radio Astronomy Observatory. Karl G. Jansky VLA. We observed two clump locations within the IRDC G32.02+0.06, an active clump ([ℓ, b] = [32:032, +0:059]) and a quiescent clump ([ℓ, b] = [31:947, +0:076]), see Figure 1. The active clump displays signs of active star formation, including a 6.7 GHz methanol maser (Pestalozzi et al. 2005), 8 and 24 μm emission, as well as radio continuum emission (see Battersby et al. 2014; White et al. 2005; Helfand et al. 2006) indicative of Ultra-Compact H II Regions. The quiescent clump does not show any of those star formation signatures, except for the possible association with a faint 24 μm point source. The final beam FWHM produced by the model was about 4.4′ (~0.1 pc at the adopted distance of 5.5 kpc, Battersby et al. 2014) and an rms noise of about 6 mJy beam−1.

The gas physical properties were derived from the inversion transitions using radiative transfer modeling of the lines. The ammonia lines were fit with a Gaussian line profile to each hyperfine component simultaneously with frequency offsets fixed. The fitting was performed in a Python routine translated from Erik Rosolowsky’s IDL fitting routines (Section 3 of Rosolowsky et al. 2008). The model was used within the framework of the pysteckit spectral analysis code package (Ginsburg & Mirocha 2011, http://pysteckit.bitbucket.org). Typical statistical errors are in the range σ(TK) ~ 1–3 K for the kinetic temperature, and σ (log[Σ(N(NH3))]) ~ 0.05 (about 10% in N(NH3)) for the column density of ammonia. See Battersby et al. (2014) for more details.

2.2. Dust Continuum Column Density

2.2.1. Herschel Infrared Galactic Plane Survey

Hi-GAL (Molinari et al. 2010) is an Open Time Key Project of the Herschel Space Observatory (Pilbratt et al. 2010). Hi-GAL has performed a five-band photometric survey of the Galactic plane in a |b| ≤ 1° -wide strip from −70° ≤ ℓ ≤ 70° at 70, 160, 250, 350, and 500 μm using the Photodetector Array Camera and Spectrometer (PACS; Poglitsch et al. 2010) and Spectral and Photometric Imaging Receiver (SPIRE; Griffin et al. 2010) imaging cameras in parallel mode. Data reduction was carried

![Figure 1. Images depicting the two clumps studied in this work. The images are three-color in the mid-IR (MIPS GAL, GLIMPSE, Red: 24 μm, Green: 8 μm, Blue: 4.5 μm) with column density contours derived from NH3 (six linearly spaced contours, in the quiescent clump from 8×10^21 cm^{-2} to 3×10^23 cm^{-2}).](Image)
out using the *Herschel* Interactive Processing Environment (Ott 2010) with custom reduction scripts that deviated considerably from the standard processing for PACS (Poglitsch et al. 2010), and to a lesser extent for SPIRE (Griffin et al. 2010). A more detailed description of the entire data reduction procedure can be found in Traficante et al. (2011). A weighted post-processing on the maps (Piazza 2013) has been applied to help with image artifact removal.

We use the Hi-GAL data to derive dust continuum column densities and temperatures at 36′ resolution using pixel-by-pixel modified blackbody fits to the SPIRE 250, 350, and 500 μm data. Generally, the PACS 160 μm data are also part of the modified blackbody fit (as in Battersby et al. 2011), however, the quiescent clump has an exceptionally cold temperature and relatively low column density, such that the PACS 160 μm point is lower than the background (this happens in less than ~5% of pixels) and so that point is not included. The fits are very similar both qualitatively and quantitatively with and without the PACS 160 μm point (within about 10% in column density and about 3% in temperature).

The modified blackbody fits are performed on data that has had the cirrus foreground subtracted using an iterative routine discussed in detail in Battersby et al. (2011). The modified blackbody fits assume a spectral index, β, of 1.75, a gas to dust ratio of 100, a mean molecular weight of 2.8 (e.g., Kauffmann et al. 2008), and the Ossenkopf & Henning (1994) MRN distribution model with thin ice mantles that have coagulated at 106 cm−3 for 1013 yr for the dust opacity. As in Battersby et al. (2011), we fit a power-law to the Ossenkopf & Henning (1994) dust opacity to have a continuous dust opacity as a function of wavelength. This power-law fit gives us a dust opacity of 5.4 cm2 g−1 at 500 μm (compared with 5.0 cm2 g−1 from Ossenkopf & Henning 1994) and a value of β of 1.75.

2.2.2. Bolocam Galactic Plane Survey

We utilize the 1.1 mm dust continuum emission from version 2 of the BGPS (Ginsburg et al. 2013; Aguirre et al. 2011; Rosolowsky et al. 2010) to estimate the isothermal column densities. We derive column density maps at 33′ resolution assuming the dust temperature from the corresponding pixel in Hi-GAL. The column density is given by

\begin{equation}
N(H_2) = \frac{S_\nu}{\Omega_B \kappa_\nu B_\nu(T) \mu_{H_2} m_{H_2}}
\end{equation}

(1)

\begin{equation}
N(H_2)_{1,1mm} = 2.20 \times 10^{22} (\frac{\nu^{13}}{10^2} - 1) S_\nu \text{ cm}^{-2}
\end{equation}

(2)

where \( S_\nu \) is the source flux (in Jy in Equation (2)), \( B_\nu(T) \) is the Planck function at dust temperature \( T \), \( \Omega_B \) is the beam size, and \( \mu_{H_2} \) is the mean molecular weight for which we adopt a value of 2.8 (Kauffmann et al. 2008). We adopt a value of \( \kappa_{1,1mm} = 1.14 \text{ cm}^2 \text{ g}^{-1} \), interpolated from the tabulated values of dust opacity from the Ossenkopf & Henning (1994) MRN distribution model with thin ice mantles that have coagulated at 106 cm−3 for 1013 yr. This same model for dust opacity was used for the Hi-GAL and 8 μm extinction-derived column densities. We assume a gas-to-dust ratio of 100. We use the dust temperatures derived from Hi-GAL in each pixel above in the calculation of the column densities. The same analysis is possible with ATLASGAL 870 μm (Schuller et al. 2009) or SCUBA-2 850 um data (Chapin et al. 2013), which, like the Bolocam data, trace column density and are relatively insensitive to the dust temperature. However, at the time the analysis was performed, no data sets from these instruments were available.

2.3. Extinction Derived Column Density

Dense clumps of dust and molecular gas will absorb the bright mid-IR Galactic background and appear as dark extinction features in the mid-IR (e.g., Carey et al. 1998; Egan et al. 1998; Peretto & Fuller 2009). We use data from the GLIMPSE (Benjamin et al. 2003) to derive column density maps from the extinction of the dense clumps at 8 μm at 2′ resolution. The extinction mass and column density are calculated using the Butler & Tan (2009) method with the correction as applied in Battersby et al. (2010). We use a dust opacity (κ8μm = 11.7 cm2 g−1) from the same Ossenkopf & Henning (1994) model as above, which is a reasonable model for the cold, dense environment of an IRDC. This and the assumption of a gas-to-dust ratio of 100 is consistent with the opacity used for our dust emission column density estimates. This method uses an 8 μm extinction-derived model of the Galaxy and the cloud distance to solve the radiative transfer equation for cloud optical depth. The expression for the gas surface density is

\begin{equation}
\Sigma = \frac{1}{\kappa_\nu} \left[ \frac{(s + 1) I_{1, obs} - (s + f_{\text{fore}}) I_{0, obs}}{(1 - f_{\text{fore}}) I_{0, obs}} \right],
\end{equation}

(3)

where \( \kappa_\nu \) is the dust opacity, \( I_{1, obs} \) and \( I_{0, obs} \) are the observed intensities in front of and behind the cloud, respectively, \( s \) is the IRAC scattering correction (0.3; see Battersby et al. 2010), and \( f_{\text{fore}} \) is the fraction of total emission along the line of sight produced in the foreground of the cloud (0.3 for this cloud at the kinematic distance of 5.5 kpc). We compare this estimate with the method using the 8 μm extinction-derived column density from Peretto & Fuller (2009). The Peretto & Fuller (2009) method assumes that most of the observed 8 μm emission is local to the cloud, so a distance is not required. For this particular source, the column densities derived using the Peretto & Fuller (2009) method are about 15% higher than the Butler & Tan (2009) method, with very little scatter. We use the Butler & Tan (2009) method for the remainder of the discussion.

2.4. GRS 13CO Column Density

We utilize data taken as part of the BU-FCRAO GRS or just GRS (Jackson et al. 2006) of the 13CO J = 1–0 transition at 46′ resolution to calculate a column density assuming a gas temperature from the corresponding pixel in the NH3 gas temperature map. In the optically thin, thermalized limit, the H2 column density derived from 13CO is given by

\begin{equation}
N(H_2) = \frac{8\pi \nu^3 X_{13CO}}{3c^3 h B_J A_{10}} (1 - e^{-h
u/kT_{ex}})^{-1} \int T_{mb} \, d\nu
\end{equation}

(4)

where ν is the frequency of the 13CO J = 1–0 transition, \( A_{10} \) is the Einstein A coefficient of 13CO from state J = 1 to J = 0, \( T_{ex} \) is the excitation temperature, \( B_J \) is the rotation constant, and \( X_{13CO} \) is the abundance fraction of 13CO to H2. We adopt a value of 12CO/13CO of 58 from Lucas & Liszt (1998), and a value of 12CO/H2 of 10−4, a value of 55.101038 GHz for \( B_J \), and standard NIST values for all constants and spectral transition values. This expression then reduces to

\begin{equation}
N(H_2) = 1.45 \times 10^{20} \frac{\int T_{mb} \, d\nu}{1 - e^{-5.29/T}} \text{ cm}^{-2},
\end{equation}

(5)
Figure 2. Correlation of column densities derived from various independent data sets vs. the ammonia column density for the abundance calculation. Column densities are derived from Hi-GAL and BGPS 1.1 mm dust continuum emission (using dust temperatures derived from Hi-GAL), $^{13}$CO integrated intensity, and $8 \mu m$ extinction and are plotted on the $x$-axis against the NH$_3$ integrated intensity column density on the $y$-axis. The left plot shows pixels within the quiescent clump, while the right shows the active clump. Both dust continuum emission tracers show good correlation with the NH$_3$ emission, however, with a systematic offset. The $8 \mu m$ extinction estimate shows excellent morphological agreement on large scales but the correlation on small scales is highly scattered (gray points show all data and magenta points show their average over 15 pixels for comparison). The details of these plots are discussed in Section 3. Linear fits are shown for the BGPS ($\textit{in blue}$) and Hi-GAL ($\textit{in orange}$) points. We also show two abundance lines for comparison, $\chi_{\text{NH}_3} = 8.1 \times 10^{-7}$ from Ragan et al. (2011) and $\chi_{\text{NH}_3} = 4.6 \times 10^{-8}$ from this work and Pillai et al. (2006).

(A color version of this figure is available in the online journal.)

assumptions on how we derive a column density estimate from $^{13}$CO, see Section 3.5 of Battersby et al. (2010).

3. ABUNDANCE AND THE CORRELATION OF $N$(NH$_3$) WITH $N$(H$_2$)

An abundance measurement of NH$_3$ ($\chi_{\text{NH}_3} = (N$(NH$_3$)/$N$(H$_2$))) can be derived from a comparison of the derived NH$_3$ column densities to the H$_2$ column densities from a variety of independent measurements: dust continuum emission, dust extinction, and $^{13}$CO line emission. The dust continuum column densities are derived as described in Section 2.2 using Hi-GAL and BGPS (36$''$ and 33$''$ resolution, respectively) with dust temperatures from Hi-GAL (Battersby et al. 2011). The dust-extinction-derived column density is calculated using $8 \mu m$ extinction, as described in Section 2.2.1 with 2$''$ resolution. We also utilize $N$(H$_2$) derived from $^{13}$CO (as described in Section 2.4) using the NH$_3$ gas temperatures, despite the $^{13}$CO’s much lower resolution at 46$''$.

For a pixel-by-pixel comparison with the NH$_3$ column density maps in the quiescent and active clump, we convolve and regrid the higher resolution data (the NH$_3$ column density maps in all cases except the $8 \mu m$ extinction) to match the lower resolution data for each clump. The pixel-by-pixel comparison is shown in Figure 2. While there is a good deal of scatter, there also appear to be systematic differences in the column densities derived from the different methods. We briefly comment on the magnitude and possible reasons for these differences below. These systematic disagreements should help to give a flavor for the uncertainties involved in such measurements; Battersby et al. (2010) conclude that typical mass uncertainties using such tracers are about a factor of two.

For each clump and each H$_2$ tracer we fit a line between $N$(NH$_3$) and $N$(H$_2$). The data were fit using the total least squares method, which takes into account errors on both the $x$ and $y$ data points (unlike ordinary least squares, which assumes no error on the $x$ data). The errors were assumed to be 50% of the column values for both the NH$_3$ and total column density. We first fit a line with the NH$_3$ $y$-intercept fixed at zero (the typical method for determining abundances), then fit a line allowing for a non-zero $y$-intercept. We only include points with $N$(H$_2$) between $10^{20}$ and $10^{24}$ cm$^{-2}$ which also fit the “mask” criteria applied to all the NH$_3$ data as described in our companion paper, Battersby et al. (2014). We exclude a handful of noisy pixels near the edges of the maps. The results of the fits are shown in Table 1.

**Hi-GAL.** The Hi-GAL column densities show a good correlation with the NH$_3$ data. The average derived NH$_3$ abundance is about $4.6 \times 10^{-8}$, or with a non-zero $y$-intercept, about $3.3 \times 10^{-8}$ with an NH$_3$ intercept of about $3.9 \times 10^{14}$ cm$^{-2}$. Rather than harboring any physical meaning, this non-zero intercept likely indicates that the abundance relationship is not well described by a single linear fit for all column densities.

**BGPS.** The BGPS column densities also show a good correlation with the NH$_3$ column densities. The average abundance is about $8.6 \times 10^{-8}$ fixing the $y$-intercept at zero, or $5.7 \times 10^{-8}$ with an intercept of about $4 \times 10^{14}$ cm$^{-2}$. There is a factor of two systematic offset of the BGPS column densities from the Hi-GAL measured column densities, which can be plausibly explained by several smaller factors (see Section 3.1).

**8 \mu m Dust Extinction.** The NH$_3$ and $8 \mu m$ dust extinction show excellent morphological agreement (as seen in our companion paper, Battersby et al. 2014); the masks created using a column density threshold for each of them are nearly identical. However, comparing their column densities within those masks reveals a great deal of scatter. All the data points are plotted in gray in Figure 2, and their averages (on 15$''$ scales to show less scatter) are shown in magenta. A few interesting things to note are as follows. (1) We do not find any extinction-derived column densities greater $N$(H$_2$) $\sim 3.5 \times 10^{22}$ cm$^{-2}$ with a somewhat
significant cutoff at this column density. This cutoff is likely due to the increasing optical depth of the 8 μm emission which would saturate the extinction measurement. Using our dust opacity at 8 μm of 11.7 g cm$^{-2}$ (see Section 2.3), $\tau_{8\mu m} = 1$ at $N(H_2) \approx 2 \times 10^{22}$ cm$^{-2}$, which, given reasonable systematic error estimates, can easily explain the observed cutoff. (2) The active clump is a bit warmer and has a brighter local 8 μm background, which fills in some of the absorption, explaining the low extinction derived column densities in that region. (3) Variations in the NH$_3$ abundance, 8 μm background, and/or dust opacity are likely responsible for the large scatter in the extinction-derived column densities, despite their high resolution. The ratio of extinction to BGPS column densities is about the same as found in Battersby et al. (2010), with a ratio of 0.5 (originally 0.7, now 0.5 with the 1.5 correction factor to BGPS v2) in the active clump and a ratio of about 1.3 (originally 2.0, now 1.3 with 1.5 correction factor to BGPS v2) in the quiescent clump.

**GRS.** While we would not expect to find a very strong correlation in column density over the few resolution elements the GRS $^{13}$CO has over the VLA field of view, the comparison of the overall column densities is informative. The total column density derived from $^{13}$CO GRS is about half that from Hi-GAL and slightly less than the BGPS (about 90%). Whether this indicates CO depletion, optically thick $^{13}$CO, or some other physical effect cannot be determined from these data alone. This is representative of typical systematic errors of a factor of two in column density determinations.

We adopt the average Hi-GAL-derived abundance of $\chi_{NH_3} = 4.6 \times 10^{-8}$ throughout the remainder of this analysis. Since the Hi-GAL column densities are derived simultaneously with the dust temperature, and utilize data at multiple wavelengths to perform full modified blackbody fits, we consider that these column densities may be more robust than those determined at a single wavelength with an assumed temperature. We note, however, that BGPS-derived column densities would be less susceptible to gradients in the dust temperature. Additionally, the conditions probed with the Hi-GAL data (dust continuum emission from cold, dense clumps) are roughly the same conditions probed with NH$_3$ (dense gas emission from cold, dense clumps), making the Hi-GAL data a reasonable choice for the derivation of NH$_3$ abundance. We do not see significant evidence of NH$_3$ depletion. If the difference in the measured Hi-GAL NH$_3$ abundance between the quiescent and active clump is due to depletion, then the NH$_3$ is depleted by about 30% in column density in the quiescent clump; see Figure 5.

Our measured average abundance, $\chi_{NH_3} = 4.6 \times 10^{-8}$, is very close to that derived by Pillai et al. (2006) in IRDCs. Additionally, Dunham et al. (2011) studied the abundance of ammonia as a function of Galactocentric radius and found a decrease in abundance of a factor of seven from a radius of 2–10 kpc. Given the Galactocentric radius of the IRDC studied here (4.7 kpc), the relationship determined by Dunham et al. (2011) predicts an abundance of $4.5 \times 10^{-8}$, which is in agreement with both the abundance determined in this study and the recent abundance determination toward this cloud by Chira et al. (2013). One major difference is that Pillai et al. (2006); Dunham et al. (2011); Chira et al. (2013) use single-dish NH$_3$ observations of two NH$_3$ lines, while we use interferometric observations of NH$_3$ modeled with three lines, all para-NH$_3$. Our higher resolution observations are probing smaller spatial scales and therefore deriving higher average column densities toward the densest regions, however, we are also insensitive to spatial scales above 66′. The high-resolution observations are probing the densest gas on small spatial scales, while the single-dish observations are probing all the gas in the beam. The fact that the abundance measurements are consistent between the observations suggests that either this abundance ratio is constant for the range of diffuse to dense gas that is being probed by both or that the NH$_3$ and dust we are probing with both

### Table 1

**Abundance Measurements**

| Comparison of $N(NH_3)$ with $N(H_2)$ | $\chi_{NH_3}$ | $\chi_{NH_3}$ with Intercept | NH$_3$ Intercept | (cm$^{-2}$) |
|--------------------------------------|---------------|-------------------------------|-----------------|------------|
| Quiescent clump                      |               |                               |                 |            |
| Hi-GAL                               | 4.0e-8 ± 0.2e-8 | 3.0e-8 ± 0.7e-8               | 3e14 ± 2e14     |            |
| BGPS                                 | 8.6e-8 ± 0.8e-8 | 3.9e-8 ± 0.7e-8               | 4.8e14 ± 0.7e14 |            |
| 8 μm extinction                      | 4.6e-8 ± 0.09e-8 | 9.3e-8 ± 0.4e-8               | −7.4e14 ± 0.7e14 |            |
| GRS $^{13}$CO                         | 9.5e-8 ± 0.2e-8 | 1.9e-7 ± 0.6e-8               | −1.2e15 ± 0.8e15 |            |
| Active clump                         |               |                               |                 |            |
| Hi-GAL                               | 5.3e-8 ± 0.2e-8 | 3.6e-8 ± 0.6e-8               | 9e14 ± 3e14     |            |
| BGPS                                 | 8.7e-8 ± 0.3e-8 | 7.5e-8 ± 0.8e-8               | 4e14 ± 2e14     |            |
| 8 μm extinction                      | 2.19e-7 ± 0.04e-7 | 2.46e-7 ± 0.08e-7             | −2.3e14 ± 0.7e14 |            |
| GRS $^{13}$CO                         | 1.1e-7 ± 0.2e-7 | −1.8e-6 ± 0.6e-6              | 6e16 ± 2e16     |            |

**Notes.**

a NH$_3$ abundance: linear fit to data without a y-intercept.
b Assuming a column density error of 20%.
c NH$_3$ abundance: linear fit to data with a y-intercept.
d NH$_3$ column density intercept of the fit to the abundance.

3.1. The BGPS and Hi-GAL Discrepancy

In comparing the column densities derived from various data sets, we find a systematic offset of about 2 from Hi-GAL- to

Our measured average abundance, $\chi_{NH_3} = 4.6 \times 10^{-8}$, is very close to that derived by Pillai et al. (2006) in IRDCs. Additionally, Dunham et al. (2011) studied the abundance of ammonia as a function of Galactocentric radius and found a decrease in abundance of a factor of seven from a radius of 2–10 kpc. Given the Galactocentric radius of the IRDC studied here (4.7 kpc), the relationship determined by Dunham et al. (2011) predicts an abundance of $4.5 \times 10^{-8}$, which is in agreement with both the abundance determined in this study and the recent abundance determination toward this cloud by Chira et al. (2013). One major difference is that Pillai et al. (2006); Dunham et al. (2011); Chira et al. (2013) use single-dish NH$_3$ observations of two NH$_3$ lines, while we use interferometric observations of NH$_3$ modeled with three lines, all para-NH$_3$. Our higher resolution observations are probing smaller spatial scales and therefore deriving higher average column densities toward the densest regions, however, we are also insensitive to spatial scales above 66′. The high-resolution observations are probing the densest gas on small spatial scales, while the single-dish observations are probing all the gas in the beam. The fact that the abundance measurements are consistent between the observations suggests that either this abundance ratio is constant for the range of diffuse to dense gas that is being probed by both or that the NH$_3$ and dust we are probing with both measurements arises primarily from dense gas on small scales. These abundances are also consistent with previous literature values of $3 \times 10^{-8}$ and $6 \times 10^{-8}$ from Wang et al. (2008) and $3 \times 10^{-8}$ from Harju et al. (1993). Our adopted abundance, $\chi_{NH_3} = 4.6 \times 10^{-8}$, differs from the interferometrically derived 8 μm-extinction-based abundance of $8.1 \times 10^{-7}$ by Ragan et al. (2011) in IRDCs, but given the large scatter in our extinction-derived abundances (average of $1.1 \times 10^{-7}$), the disagreement is not too surprising.
BGPS-derived column densities (Hi-GAL-derived column densities are, on average, about two times higher). We suggest that a handful of smaller effects can explain this offset. Because the atmospheric subtraction used for BGPS filters out large-scale structures, Hi-GAL is more sensitive to larger spatial scales. Due to this difference in derivation of large scale structure, despite the background subtraction, we might still expect slightly lower values in the BGPS due to spatial filtering (perhaps of the order of 20%). We have checked and confirmed that the difference does not arise from the convolutions or re-gridding of the data. While both use the same model for the dust opacity (Ossenkopf & Henning 1994), the power-law fit opacity used for Hi-GAL extrapolated from Ossenkopf & Henning (1994) is slightly higher (0.0135 using a power-law fit and $\beta = 1.75$ versus 0.0114, linearly interpolating tabulated values near 1.1 mm, about $1.2 \times$ higher) at 1.1 mm than the tabulated value used in the BGPS column density. The Hi-GAL procedure required a dust opacity that was a continuous function of frequency so we used a power-law fit to Ossenkopf & Henning (1994) dust opacity rather than the tabulated value. Additionally, the spectral index $\beta$ may be steeper than the assumed value of 1.75. If we assume that about 20% of the total flux is lost in BGPS due to spatial filtering and use the Hi-GAL power-law extrapolated opacity at 1.1 mm, and assume a spectral index of $\beta$ slightly steeper than 2 (about 2.25), then we can bring the two column densities into agreement. The large systematic offset can be plausibly explained by a few smaller effects that all push the BGPS column density to lower values.

4. A COMPARISON OF THE DUST AND GAS PROPERTIES

We present a comparison of Hi-GAL dust-derived temperatures and column densities with those derived from NH$_3$ on the VLA shows good correlation except for the gas and dust temperatures in the quiescent clump. The magenta and blue points show the active and quiescent clump pixels, respectively, which have had the background subtracted and have been used throughout the text, while the orange and green points show the active and quiescent clump pixels, respectively, which have not had the background subtracted for comparison. Left: the dust vs. gas temperature for both clumps. The two show reasonable correlation, though with much scatter, for the active clump and no correlation for the quiescent clump. A typical model fit error bar (2 K in both $T_{\text{dust}}$ and $T_{\text{gas}}$ is shown in the bottom right). See the discussion in Section 4. Right: the column densities are reasonably well-correlated over a wide range. A typical model fit error bar (10% in $N(\text{NH}_3)$, $1 \times 10^{22}$ cm$^{-2}$ in $N(\text{H}_2)$) is shown at three points throughout the plot (to give a sense of errors in the log-log plot).

(A color version of this figure is available in the online journal.)
We estimate volume densities by assuming that the line-of-sight structure sizes are about the same as the observed plane-of-the-sky structure sizes. We divide both the quiescent and active clump maps into “core” and “filament” pixels and use appropriate plane-of-the-sky structure sizes for each to translate the NH$_3$ column densities into volume densities. The size estimates used are approximate and reflect the effective plane-of-the-sky structure sizes. We divide both the quiescent and gas temperatures separately, especially at early times and densities $n < 10^5$ cm$^{-3}$ may be important. This agreement lends some support for a lifetime for the currently observed and previously existing IRDC phase of order 0.5 Myr (similar to the 0.6–1.2 Myr starless lifetime found by C. Battersby et al., in preparation).

5. COMPARISON WITH THE SINGLE-DISH GBT DATA

The gas temperatures and column densities found here agree with the single-dish GBT results found by Dunham et al. (2011) in a survey of NH$_3$ toward BGPS clumps. The VLA results presented here have a resolution roughly 10 times better than the BGPS, and are able to detect smaller, higher density regions within the large-scale BGPS clump.

In the quiescent clump, the VLA observations returned a gas kinetic temperature of 8–15 K for the filament and 13 K for both the Main (Core 1) and Secondary cores (Cores 2, 3, and 4). The single-dish data in this region centered on the peak of BGPS source number 4901, which is very close to Core 1 in the VLA data. The single-dish data returned a gas kinetic temperature of 14.9 K, which is slightly warmer than the VLA data because the GBT beam also included a significant amount of the surrounding warmer filament gas within the 31″ beam.

In the active clump, the hot core and cold core complexes, as well as the UCHII region all fall within a single BGPS source (BGPS source number 4916 in v1 of the catalog). In particular, the hot core complex corresponds to the position of the single-dish data. The single-dish gas temperature is slightly lower than the VLA-derived gas temperature (30.4 K and 35–40 K, respectively). This difference can be explained in the same way as the difference in the quiescent clump: the single-dish observations include some of the surrounding cooler gas which lowers the derived kinetic temperature. Although the exact numbers differ between this study and the single-dish study, the results are consistent. This comparison highlights simple in these young star-forming clumps, even at $10^{4.5}$ cm$^{-3}$.
the hierarchical nature of star formation, showing increasing complexity and sub-structure down to our resolution limit.

6. THE HIGH-RESOLUTION ORIGIN OF SUBMILLIMETER CLUMP EMISSION

The high-resolution NH₃ data from the VLA allows the unique opportunity to explore the properties of dense gas on subparsec scales. The BGPS, on the other hand, allows for an investigation of these properties across the Galaxy, but on ≥ 1 pc scales (33″ resolution corresponds to clumps on the near side of the Galaxy or whole clouds on the far side). A comparison of this high resolution NH₃ data with large-scale BGPS data allows an opportunity to address the small-scale origin of the millimeter flux throughout the Galaxy.

In this particular IRDC, the contribution of free-free emission to the millimeter flux is negligible (Battersby et al. 2014), as the only radio continuum source (G32.03+0.05) observed at 1, 6 and 20 cm is not coincident with the millimeter emission; the source is evolved enough to have blown out most of the dense gas and dust. In order to determine the relative contributions of the cores and filaments to the millimeter flux, we invert Equation (2) in Section 2.2, the equation to derive the dust column density from millimeter flux, and solve it for the millimeter flux using the column density and temperature maps derived from the NH₃ data. This gives us a simulated map of 1.1 mm flux on subparsec scales. This, of course, assumes a tight coupling between the dense gas and dust. If the gas and dust are less well-coupled, especially in the lower density filaments, then we are overestimating the flux from the filament (if the dust is colder than we are assuming), and a higher fraction of the millimeter emission arises from the dense gas cores. In the quiescent clump, where we think that the true dust temperature is lower than the measured gas temperature (12 K versus 15 K), the simulated fluxes at 1.1 mm would be about 70% of what is reported here. The fractions, however, remain unchanged as they are relative to the total.

In Figures 6 and 7, we measure which structures are responsible for the observed parsec-scale sub-millimeter emission observed at 1.1 mm with the BGPS. We compare the simulated (forward-modeled) 1.1 mm flux with the real 1.1 mm BGPS flux and find that in the quiescent clump, about 55% of the global real BGPS 1.1 mm flux is filtered out by the interferometer/masking, meaning that only about 45% of the real BGPS 1.1 mm flux arises from dense filaments with \( N(H_2) > 1 \times 10^{22} \text{ cm}^{-2} \). In the active clump, the gas is more compact and all of it appears to arise from structures with \( N(H_2) > 10^{22} \text{ cm}^{-2} \) (i.e., the simulated subparsec 1.1 mm flux matches the real parsec-scale 1.1 mm flux). About 7% versus 72% of the total 1.1 mm flux arises from massive star-forming dense cores for the quiescent and active clumps, respectively, where massive star-forming cores refers to being above the massive star-forming threshold from Krumholz & McKee (2008), which corresponds very roughly to \( N(H_2) > 7.3 \times 10^{22} \text{ cm}^{-2} \) for one resolution element in our maps. About 0% versus 20% of the total 1.1 mm flux arises from the densest cores with \( \Sigma > 1 \text{ g cm}^{-2} \) in the quiescent and active clumps, respectively, the theoretical threshold for the formation of massive stars from Krumholz & McKee (2008), corresponding to about \( N(H_2) > 21 \times 10^{22} \text{ cm}^{-2} \).

In summary, submillimeter BGPS clumps show a variety of subparsec structure and the origin of 1.1 mm emission can be from diffuse clumps, dense filaments, and massive star-forming cores. In some clumps (like the quiescent clump), over 50% of the flux arises from the diffuse clump, about 40% from the dense...
filament, and only about 10% from massive star-forming cores. In other clumps (like the active clump), all of the submillimeter flux arises from dense filamentary structures with $N(\text{H}_2) > 10^{22} \text{ cm}^{-2}$ and about 75% from massive star-forming cores, in a range of evolutionary states. Submillimeter dust clumps probe a range of density structures and star-forming evolutionary states. The fact that the more evolved clump contains a significantly larger dense gas fraction than the quiescent clump is an interesting result. This fraction may be a meaningful measure of the global collapse of a clump, however, a larger sample is required to address this correlation.

7. CONCLUSIONS

We explore the relationship between dust and gas derived physical properties in a massive star-forming IRDC, G32.03+0.05 showing a range of evolutionary states. The gas properties (temperature and column density) were derived using radiative transfer modeling of three inversion transitions of para-$\text{NH}_3$ on the VLA, while the dust properties (temperature and column density) were derived with cirrus-subtracted modified blackbody fits to Herschel data. We derive an $\text{NH}_3$ abundance and compare different tracers of column density (dust emission and extinction and gas emission). The gas and dust temperatures agree well in the active clump, but the disagreement in the quiescent clump calls into question either the reliability of dust temperatures in this regime or the assumption of tight gas and dust coupling. We also explore the high-resolution ($\sim$0.1 pc) origin of parsec-scale dust emission by forward modeling the gas temperature and column densities to derive 1.1 mm fluxes and comparing with the observed BGPS 1.1 mm fluxes.

1. $\text{NH}_3$ abundance. A comparison of the $\text{NH}_3$ column density with those derived from various independent tracers exemplifies some of the uncertainties involved in such measurements, as the systematic variations between these tracers is about a factor of two. The Hi-GAL dust continuum data show a good correlation with the $\text{NH}_3$ from which we derive an abundance of $\chi_{\text{NH}_3} = 4.6 \times 10^{-8}$, in agreement with previous single-dish observations. This agreement indicates that both the gas and dust are clumpy on scales smaller than about 60$''$ (the largest angular size to which our $\text{NH}_3$ observations are sensitive).

2. Gas and dust coupling. The gas and dust column densities show good agreement. Depletion of $\text{NH}_3$ in the quiescent clump is of the order of 30% or less. The dust and gas temperatures are scattered, but agree reasonably well for the active clump (within about 20%). The quiescent clump, however, shows no correlation between dust and gas temperature. At lower densities in the quiescent clump, the two may not be well-coupled, or we may be probing a regime in which the dust or $\text{NH}_3$ temperature estimates break down. A comparison of these temperatures and densities agrees well with a cluster-scale star formation simulation (Martel et al. 2012) just before the stars begin to turn on (about 0.5 Myr). The agreement of our observations with this simulation suggests that simulating the gas and dust heating and cooling processes individually in young star-forming regions may be important.

3. The origin of dust continuum emission. Forward modeling of the $\text{NH}_3$ data (temperatures and column densities) to produce millimeter fluxes and comparing these with BGPS millimeter fluxes reveals that millimeter dust continuum observations, such as the BGPS, Hi-GAL, and ATLASGAL, probe hot cores, cold cores, as well as the dense filaments from which they form. The millimeter flux is not dominated by a single hot core, but rather, is representative of the cold, dense gas as well. We estimate that the quiescent clump is dominated by diffuse emission, much of which

![Figure 7](image-url)
(about 55%) is filtered out by the interferometer in our VLA measurements. In this clump, the cold, dense filament comprises about 45% of the total flux. Only about 7% of the total 1.1 mm flux arises from massive star-forming cores in the quiescent clump. The active clump is dominated by high density gas, both hot and cold, in the form of dense filaments (100% of the flux from material with $N(H_2) > 10^{22}$ cm$^{-2}$) and massive star-forming cores (72% of the flux from massive star-forming cores; $N(H_2) > 7.3 \times 10^{22}$ cm$^{-2}$ and 20% from material with $N(H_2) > 2.1 \times 10^{23}$ cm$^{-2}$).

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