The Green Bank Ammonia Survey: First Results of NH₃ Mapping of the Gould Belt

Rachel K. Friesen¹, Jaime E. Pineda² (co-PIs), and
e Erik Rosolowsky⁵, Felipe Alves², Ana Chacón-Tanarro², Hope How-Huan Chen⁴, Michael Chun-Yuan Chen⁵, James Di Francesco⁵, Jared Keown⁵, Helen Kirk⁸, Anna Punanova⁵, Youngmin Seo⁷, Yancy Shirley⁸, Adam Ginsburg⁹, Christine Hall¹⁰, Stella S. R. Offner¹¹, Ayushi Singh¹², Héctor G. Arce¹³, Paola Caselli², Alyssa A. Goodman⁴, Peter G. Martin¹⁴, Christopher Matzner¹², Philip C. Myers⁴, Elena Redaelli¹²,¹⁵ (The GAS Collaboration)

¹ Dunlap Institute for Astronomy & Astrophysics, University of Toronto, 50 St. George Street, Toronto, ON M5S 3H4, Canada
² Max-Planck-Institut für extraterrestrische Physik, Giessenbachstrasse 1, D-85748 Garching, Germany
³ Harvard-Smithsonian Center for Astrophysics, 60 Garden St., Cambridge, MA 02138, USA
⁴ Harvard-Smithsonian Center for Astrophysics, 60 Garden St., Cambridge, MA 02138, USA
⁵ Department of Physics and Astronomy, University of Victoria, 3800 Finnerty Road, Victoria, BC V8P 5C2, Canada
⁶ Department of Physics and Astronomy, University of Victoria, 3800 Finnerty Road, Victoria, BC V8P 5C2, Canada
⁷ Jet Propulsion Laboratory, NASA, 4800 Oak Grove Drive, Pasadena, CA 91109, USA
⁸ Steward Observatory, 933 North Cherry Avenue, Tucson, AZ 85721, USA
⁹ National Radio Astronomy Observatory, Socorro, NM 87801, USA
¹⁰ Department of Physics, Engineering Physics & Astronomy, Queen’s University, Kingston, ON K7L 3N6, Canada
¹¹ Department of Astronomy, University of Massachusetts, Amherst, MA 01003, USA
¹² Department of Astronomy & Astrophysics, University of Toronto, 50 St. George Street, Toronto, ON M5S 3H4, Canada
¹³ Department of Astronomy, University of Toronto, 50 St. George Street, Toronto, ON M5S 3H4, Canada
¹⁴ Department of Physics, Engineering Physics & Astronomy, University of Toronto, 50 St. George Street, Toronto, ON M5S 3H4, Canada
¹⁵ Dipartimento di Fisica & Astronomia, Università degli Studi di Bologna, Viale Berti Pichat, 6/2, I-40127 Bologna, Italy

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Abstract
We present an overview of the first data release (DR1) and first-look science from the Green Bank Ammonia Survey (GAS). GAS is a Large Program at the Green Bank Telescope to map all Gould Belt star-forming regions with A_v ≥ 7 mag visible from the northern hemisphere in emission from NH₃ and other key molecular tracers. This first release includes the data for four regions in the Gould Belt clouds: B18 in Taurus, NGC 1333 in Perseus, L1688 in Ophiuchus, and Orion A North in Orion. We compare the NH₃ emission to dust continuum emission from Herschel and find that the two tracers correspond closely. We find that NH₃ is present in over 60% of the lines of sight with A_v ≥ 7 mag in three of the four DR1 regions, in agreement with expectations from previous observations. The sole exception is B18, where NH₃ is detected toward ~40% of the lines of sight with A_v ≥ 7 mag. Moreover, we find that the NH₃ emission is generally extended beyond the typical 0.1 pc length scales of dense cores. We produce maps of the gas kinematics, temperature, and NH₃ column densities through forward modeling of the hyperfine structure of the NH₃ (1, 1) and (2, 2) lines. We show that the NH₃ velocity dispersion, σ_v, and gas kinetic temperature, T_K, vary systematically between the regions included in this release, with an increase in both the mean value and the spread of σ_v and T_K with increasing star formation activity. The data presented in this paper are publicly available (https://dataverse.harvard.edu/dataverse/GAS_DR1).

Key words: ISM: individual objects (L1668, B18, OrionA molecular complex, NGC1333) -- ISM: molecules -- stars: formation

Supporting material: figure sets

1. Introduction
The past several years have seen tremendous advancements in our ability to characterize the structure of nearby molecular clouds and the substructures in which dense star-forming cores are born. Within 500 pc of the Sun, nearly all the ongoing, predominantly low-mass star formation is contained within a ring of young stars and star-forming regions named the Gould Belt. These nearby star-forming clouds range in size and activity, from the nearly inactive Pipe Nebula, through the star-forming but largely quiescent Taurus molecular cloud, to stellar group and cluster-forming clouds such as Perseus and Ophiuchus. The Orion molecular cloud is our nearest example of a high-mass star-forming region. This variation in star formation activity, coupled with their relatively nearby distances, makes the Gould Belt clouds excellent survey targets for understanding how star formation proceeds in different environments and constraining star formation theories and simulations through detailed observations.

Consequently, the Gould Belt star-forming regions have been surveyed by several Key Programs in the infrared and submillimeter continuum. The infrared surveys have characterized the embedded young stellar populations, identifying the loci of active star formation and constraining the lifetimes of the starless and embedded stages of star-forming cores (the Spitzer Gould Belt, Spitzer Orion, and c2d surveys; Evans et al. 2003, 2009; Enoch et al. 2008; Harvey et al. 2008; Kirk et al. 2009; Megeath et al. 2012; Dunham et al. 2014). At longer wavelengths, the emission from cold dust within dense star-forming cores and the larger filaments and clumps that form the cores and young stellar.
objects (YSOs) are being surveyed extensively through Gould Belt Legacy surveys with the Herschel Space Observatory (Herschel GBS; André et al. 2010) and the James Clerk Maxwell Telescope (JCMT GBL; Ward-Thompson et al. 2007). The Herschel GBS has revealed the striking prevalence of filaments within star-forming regions, as seen in the dust emission (André et al. 2010; Könyves et al. 2010). While the presence of filaments in star-forming regions is not a new discovery (e.g., Schneider & Elmegreen 1979), their ubiquity at both low and high column densities suggests that they are integral in the buildup of the required mass to form stars. Furthermore, the Herschel GBS has found gravitationally unstable cores predominantly within (apparently) gravitationally unstable filaments. Previous studies have shown that dense molecular cores are mostly found above a visual extinction threshold of \(A_V > 5 \sim 7\) mag \((N(H_2) \sim 5\sim 7 \times 10^{21}\) cm\(^{-2}\); e.g., Onishi et al. 1998; Johnstone et al. 2004; Kirk et al. 2006). With a suggested characteristic filament width of \(<0.1\) pc (Arzoumanian et al. 2011, but see Panopoulou et al. 2017), this extinction threshold agrees within a factor of two with the critical mass per unit length of an isothermal, thermally supported cylinder \((M_{\text{line, crit}} = 16 M_{\odot} \text{pc}^{-1})\) at 10 K; Inutsuka & Miyama 1997; Hocuk et al. 2016). Therefore, understanding filament instability might be central to understanding the formation of dense cores and, consequently, stars.

If the massive and long filaments found by the Herschel GBS are an important piece of the star formation puzzle (André et al. 2014), then we must understand what their main formation mechanisms, evolutionary drivers, and fragmentation triggers are. The power of the legacy surveys described above lies in the large area coverage and consistency in observing strategies between nearby molecular clouds. A major gap in the present data is a comparable survey to characterize the dense gas properties. Continuum data show the dust column density structure but do not provide information about the gas kinematics. Kinematics and gas temperatures are key to understanding the history and future fate of star-forming material.

Kinematic studies of filaments are relatively few (e.g., Hacar & Tafalla 2011; Pineda et al. 2011; Hacar et al. 2013, 2016; Pineda et al. 2015; Henshaw et al. 2016a). The CARMA Large Area Star Formation Survey (Storm et al. 2014) targeted several regions within nearby Gould Belt clouds at higher resolution but on a smaller scale relative to the JCMT and Herschel continuum surveys. The JCMT GBLs has produced the widest survey thus far, using observations of CO (3–2) and its isotopologues to trace moderately dense gas \((10^3\text{ cm}^{-2});\) e.g., Graves et al. 2010). However, CO is frequently very optically thick, and the gas phase abundance can be severely affected by depletion onto dust grains (e.g., Caselli et al. 1999; Tafalla et al. 2002; Christie et al. 2012) in star-forming filaments and cores; therefore, it is not a useful tracer of the dense gas.

The lower \(\text{NH}_3\) metastable inversion transitions primarily trace gas of density \(n \geq 2 \times 10^3\) cm\(^{-3}\) (for gas at 10 K; Shirley 2015). Furthermore, \(\text{NH}_3\) does not typically suffer from depletion. Since \(\text{NH}_3\) observations allow us to identify actual high volume density features rather than column density peaks, \(\text{NH}_3\) is an ideal tracer of the hierarchical nature of star-forming regions and a powerful probe of the kinematics of star-forming filaments and cores.

Past \(\text{NH}_3\) observations of dense gas were primarily pencil-beam pointings or small maps around interesting targets (e.g., Jijina et al. 1999; Rosolowsky et al. 2008). The \(\text{NH}_3\)-identified cores are generally cold and quiescent (Goodman et al. 1998), either in early stages of collapse or in near-critical equilibrium (Benson & Myers 1983), and they often show significant velocity gradients (Goodman et al. 1993). The local environment influences key core properties, such as the ratio of thermal versus nonthermal motions and temperature (Myers et al. 1991; Jijina et al. 1999; Foster et al. 2009), both of which are important parameters for investigations of core stability and collapse. Larger, more sensitive maps are needed to relate the physical properties of the cores to their surrounding environment. Recent studies have highlighted the sharp transition between turbulent and thermal line widths in dense cores (Pineda et al. 2010; See et al. 2015); identified incongruities between structures identified via continuum and line emission (Friesen et al. 2009); shown that cores in more active environments, such as Orion, tend to be more unstable, despite having similar internal motions (Li et al. 2013); identified large-scale gravitational instability in a young filamentary cluster (Friesen et al. 2016); and revealed evidence for filamentary accretion in Serpens South (Friesen et al. 2013; also in \(N_2\)H\(^+\) by Kirk et al. 2013).

Here, we describe the Green Bank Ammonia Survey (GAS; co-PIs: R. Friesen and J. E. Pineda), an ambitious Large Project to survey all the major, nearby \((120 < d < 500\) pc), northern Gould Belt star-forming regions with visual extinctions \(A_V > 7\) (matching the extinction threshold for dense cores in continuum studies; e.g., Johnstone et al. 2004; Enoch et al. 2007; Lada et al. 2010) in emission from \(\text{NH}_3\), as well as the carbon-chain molecules \(C_2\)S, HC\(_5\)N, and HC\(_6\)N. Within this distance range, the GBT (Green Bank Telescope) beam at 23 GHz (32" FWHM) subtends 0.02–0.08 pc, able to resolve both the Jeans length \((0.12\) pc for \(n = 10^4\) cm\(^{-3}\) and \(T = 10\) K) and the \(<0.1\) pc typical filament width suggested by Arzoumanian et al. (2011); furthermore, it is well-matched to the resolution of the Herschel SPIRE at 500 \(\mu\)m \((\theta_{\text{beam}} = 36''\) FWHM; Griffin et al. 2010). This coordinated, large-scale survey of \(\text{NH}_3\) in the Gould Belt clouds will play a key role in understanding the evolution of dense gas in star-forming regions as a function of environment, expanding the \(\text{NH}_3\) studies described above in a consistent way; it will also complement and enhance the Gould Belt continuum surveys.

In this paper, we present the first data release (hereafter referred to as DR1) of a subset of the survey targets, describing in detail the calibration, imaging, and analysis pipelines and discussing some general trends in the data. The target regions presented are Barnard 18 (hereafter B18) in Taurus, NGC 1333 in Perseus, L1688 in Ophiuchus, and Orion A (North). Future research will focus on the key scientific goals of GAS, including analyzing the structure and stability of the dense gas, the dissipation of turbulence from large to small scales, and the evolution of angular momentum in dense cores.

In Section 2, we discuss the source selection, observations, data calibration, and imaging. In Section 3, we describe in detail the hyperfine modeling of the \(\text{NH}_3\) emission and the determination of key physical parameters of the emitting gas. In
Section 4, we present the moment maps and noise properties of the regions included in the DR1, as well as the results from the NH₃ line modeling. We present a summary in Section 5.

2. Data

2.1. Source Selection and Description

The goal of GAS was to map NH₃ emission toward all areas within the nearby (d < 500 pc), GBT-visible, star-forming molecular clouds of the Gould Belt with extinctions $A_V > 7$ mag [N(H₂) $\gtrsim 6.7 \times 10^{21}$ cm$^{-2}$, assuming $N$(H₂) = $9.4 \times 10^{20}$ cm$^{-2}$ ($A_V$ mag$^{-1}$)] (Johnstone et al. 2004; Enoch et al. 2007; Heiderman et al. 2010; Lada et al. 2010). The initial map extents were identified in each cloud using either publicly released Herschel GBS 500 μm continuum data, unreleased JCMT GBLS 850 μm continuum data, or extinction maps derived from 2MASS (Two Micron All Sky Survey) data (Dobashi et al. 2005; Ridge et al. 2006). Further refinement of mapping targets was done as new data were publicly released (e.g., Herschel GBS).

For our initial observing semester, we focused on four regions that span a range of physical environments and star formation activity: B18, NGC 1333, L1688, and Orion A (North). These regions comprise the DR1 of GAS.

B18 is a filamentary structure located in the southeast of the Taurus molecular cloud and runs roughly parallel in projection with the molecular gas structure containing Heiles Cloud 2 and the B213/L1495 filament. B18 has a projected length of $\sim 3^\circ$ ($\sim 7$ pc) with a total mass of 380–440 $M_\odot$ (Heyer et al. 1987; Mizuno et al. 1995), giving a mean gas number density $n \sim 300$ cm$^{-3}$, and it contains about nine molecular clumps as traced by CO (Heyer 1988). Based on the numbers of associated young stars, the star formation efficiency (SFE), where SFE = current $M_\star$/current $M_\text{gas}$, is $\sim 1\%$–$2\%$ (Mizuno et al. 1995).

NGC 1333 is the most active star-forming region within the Perseus molecular cloud and contains approximately 450 $M_\odot$ of molecular gas (Warin et al. 1996) and $\sim 150$ young stars (Gutermuth et al. 2008) in a region of $\sim 1$ pc$^2$. The mean gas density is therefore a few $\times 10^3$ cm$^{-3}$. Rough estimates suggest that the SFE is $\sim 13\%$–$15\%$ in the region over the past 10$^5$ yr (Walsh et al. 2006; Jørgensen et al. 2008).

L1688 is the centrally concentrated, dense hub of the Ophiuchus molecular cloud and is $\sim 1$–$2$ pc in radius and $\sim 2 \times 10^3 M_\odot$ in mass (Loren 1989). Similar to NGC 1333, the mean gas density is approximately a few $\times 10^3$ cm$^{-3}$. L1688 contains regions of extremely high visual extinction, with $A_V$ $\sim 50$–100 mag (e.g., Wilking & Lada 1983), and over 300 YSOs (Wilking et al. 2008). The SFE of the dense gas cores, identified in submillimeter continuum emission from dust, is $\sim 14\%$ (Jørgensen et al. 2008).

Orion A (North), an integral-shape filamentary structure of dense gas that extends both north and south of the Orion Nebula and its associated young stellar cluster (including the Trapezium stars), is our nearest example of ongoing high-mass star formation. The filament is characterized by varying physical conditions along the $\sim 12$ pc length mapped for DR1. A compact, narrow ridge north of the Orion Nebula, the filament becomes wider and less dense toward the south and contains a total mass of $\sim 5 \times 10^3 M_\odot$ in the area mapped here (e.g., Bally et al. 1987; Bally 2008). Overall, the star formation efficiency in Orion A is $\sim 3\%$–$5\%$ in gas with extinction $A_K > 2$, with significantly higher values (up to several tens of percent) found toward young protostellar groups and clusters (Megeath et al. 2015).

Table 1 lists the assumed distances and number of footprints (areal coverage of 10$^\prime \times 10^\prime$) completed for the GAS DR1 regions.

2.2. Observations

For all regions, observations were performed using the seven-beam K-Band Focal Plane Array (KFPA) at the GBT, with the VErsatile GBT Astronomical Spectrometer (VEGAS) backend. The GAS uses VEGAS configuration Mode 20, allowing eight separate spectral windows per KFPA beam—each with a bandwidth of 23.44 MHz and 4096 spectral channels—for a spectral resolution of 5.7 kHz, or $\sim 0.07$ km s$^{-1}$ at 23.7 GHz. All observed spectral lines are listed in Table 2. Due to limitations on the maximum separation in GHz between spectral lines in a single VEGAS bank, the GAS setup includes six spectral lines observed in each KFPA beam plus the C$_2$S $2_1 - 1_0$ line in a single central beam. Observations were performed using in-band frequency switching to maximize on-source time, with a frequency throw of 4.11 MHz.

GAS maps were generally observed in 10$^\prime \times 10^\prime$ footprints, scanning in right ascension (R.A.), with scan rows separated by 13$^\prime$ in declination (decl.) to ensure Nyquist sampling. Each 10$^\prime$ square submap was observed once. To best match the observed

### Table 1

| Cloud  | Region | Distance (pc) | Number of Footprints |
|--------|--------|---------------|----------------------|
| Taurus | B18    | 135 ± 20$^a$ | 11                   |
| Ophiuchus | 1L688 | 137.3 ± 6$^a$ | 10                   |
| Perseus | L1688 | 260 ± 26$^a$ | 8                    |
| Orion  | Orion A (North) | 414 ± 7$^a$ | 12                   |

**Notes.**

$a$ Each footprint is 10$^\prime \times 10^\prime$.

### Table 2

| Species | Transition | Rest Frequency (MHz) | Reference |
|---------|------------|----------------------|-----------|
| NH$_3$  | (1, 1)     | 23694.4955           | ...       |
| NH$_3$  | (2, 2)     | 23722.6336           | ...       |
| NH$_3$  | (3, 3)     | 23870.1296           | ...       |
| HC$_5$N | 9–8        | 23963.9010           | LOVAS     |
| HC$_5$N | 21–20      | 23687.8974(6)        | CDMS      |
| HC$_5$N | 22–21      | 24815.8772(6)        | CDMS      |
| C$_2$S  | 2$_1 - 1_0$| 22344.030(1)         | CDMS      |

**Note.** Observed in central KFPA beam only.
regions to known submillimeter continuum emission, some regions included submaps of 10′ × 5′ or 5′ × 10′ (where scans were in decl., spaced by 13″ in R.A. to minimize overheads). For all maps, the telescope scan rate was 6″/s, with data dumped every 1.044 s. A fast frequency-switching rate of 0.348 s was used to meet the proposed sensitivity per map in the time allotted, but it resulted in a small fraction (approximately a few percent) of the data being blanked due to synthesizer settling.

### 2.3. Flux Calibration

Flux calibration was performed using observations of the Moon and Jupiter. Because the Moon is large relative to the KFPA footprint, simple on-target and off-target observations allowed relative beam calibrations to be performed. In angular size, Jupiter was comparable to the 32″ GBT beam at 23.7 GHz. For these sources, nod observations were performed to alternate on- and off-source beams, cycling through all beams. Relative beam calibrations were then calculated in GBTIDL (Marganian et al. 2006).\(^{16}\) Models for each solar system target, including the effects of solar illumination and apparent size, were used to determine the expected brightness temperature in the gain analysis.\(^{17}\)

The Moon was used as the primary calibrator when available, as the planetary calibrations could vary substantially when the weather was not ideal, particularly when the on-site winds were near the 5 m/s\(^{-1}\) limits for KFPA operations at 23 GHz. This can be seen in Figure 1, where we show the beam- and polarization-averaged gains derived from observations of Jupiter and the Moon over the 15A observing semester. The Jupiter and Moon calibrations agree well when the winds are low. The last three dates when Jupiter was observed had relatively high winds (\(\gtrsim 5\) m/s\(^{-1}\)) that lowered the pointing accuracy of the telescope, which is important for obtaining an accurate flux calibration; this was ameliorated for the science observations by more frequent pointing calibration observations. Moreover, the actual telescope pointing was recorded in the position encoder positions, and these were the values used during the data cube gridding. Jupiter’s angular size over the observation dates was \(\lesssim 40″\), only slightly larger than the 32″ (FWHM) GBT beam. Small pointing errors introduced by high winds were thus able to greatly impact the derived gains. In contrast, we show in Figure 1 that the gains determined from the Moon were very stable over the 15A semester.

Figure 2 shows the gains as a function of beam and polarization, averaged over the observing semester. The final three Jupiter measurements that were impacted by winds have been omitted from the analysis. Although the gains varied between beams and polarizations, they remained consistent over the observing period. Two known targets with bright NH\(_3\) (1, 1) lines (L1489_PPC and L43) were also observed frequently in a single beam. We found that the peak line brightness varied by \(<10%\) (1-\(\sigma\)) for these sources over the semester, in agreement

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\(^{16}\) http://gbtidl.nrao.edu/

\(^{17}\) https://safe.nrao.edu/wiki/pub/GB/Knowledge/GBTMemos/GBTMemo273-11Feb25.pdf
with the calibration uncertainty estimated from our directly measured beam gain variations.

### 2.4. Data Reduction and Calibration

All GAS data reduction and imaging codes (next section) are publicly available on GitHub\(^ {18}\) and can be easily adapted for similar observations.

The data reduction was performed using a Python wrapper that called the GBT KFPA data reduction pipeline (Masters et al. 2011). The data were calibrated to main-beam brightness temperature (\(T_{\text{MB}}\)) units using the relative gain factors for each of the beams and polarizations discussed above and listed in Table 3. Based on the \(1\sigma\) variation in the beam gain calibrations, we estimate our calibration uncertainty to be \(\sim 10\%\).

\[ W(r) = \frac{J_1(\pi r / a)}{(\pi r / a)^2} e^{-r^2 / h^2} \frac{1}{\sigma_{\text{sys}}^2} \]  

(1)

Figure 3. Histograms of the rms noise maps for all lines observed toward the DR1 regions, where each observed transition is shown in a different color. The rms is on the \(T_{\text{MB}}\) scale.

2.5. Imaging

We grid the on-the-fly observations following the prescription by Mangum et al. (2007). For each region, our mapping algorithm establishes a world coordinate system and corresponding pixel grid that covers the footprint of the observations using a pixel size of one-third of the beam FWHM (\(\theta_{\text{beam}}\)) of the NH$_3$ (1, 1) line. We then calculate the value of each map pixel as the weighted average of spectra at the center of the map pixel using a truncated, tapered Bessel function for the weighting scheme. Each integration is given a weight, \(W\), based on the location of the observation relative to the center of the pixel in the resulting map and the observation rms.
where $a = 1.55(\theta_{\text{beam}}/3)$, $b = 2.52(\theta_{\text{beam}}/3)$, $r$ is the angular distance between the observed datum and the map datum, and $T_{\text{sys}}$ is the recorded system temperature. Integrations with $r > \theta_{\text{beam}}$ are excluded from the average, as suggested by Mangum et al. (2007). For simplicity of comparison, we grid the data for all lines to a common world coordinate system.

Online Doppler tracking is only applied for the NH$_3$ (1, 1) line. For all other lines, we apply a frequency shift in the Fourier domain to each individual integration to align all spectra before convolution (gridding); i.e., Doppler tracking is done in software. Baseline subtraction is done in both the individual integrations (linear baseline) and in the individual pixels in the final data cubes (Legendre polynomials of order 3). In the latter case, sections of the spectrum with significant emission or within 2 km s$^{-1}$ of the expected systemic velocity are excluded from the fit.

The KFPA on the GBT is a sparse array, with seven beams arranged in a hexagonal pattern and beam centers separated by 94.88″ on the sky. The mapping method described in Section 2.2 ensures Nyquist-spaced sampling over $10′ \times 10′$ footprints on the sky. At the edges of these footprints, coverage is variable, and the rms noise increases substantially, as noted previously. For the final moment and parameter maps for each region, we mask pixels within 3 pixels of the map edges to remove the noisiest regions.

In Figure 3, we show histograms of the rms noise for all regions and lines observed. The rms noise maps for the NH$_3$ (1, 1) observations toward each DR1 region are presented in Appendix A.

In all regions, the noise histograms have strong peaks that agree well for the NH$_3$ (1, 1), (2, 2), and (3, 3); the HC$_3$N 9 – 8; and the HC$_7$N 21 – 20 observations, with typical 1σ noise values of $< 0.1$ K per velocity channel across the DR1 regions. Note that the typical noise in individual map footprints can vary slightly depending on the conditions in which the region was mapped. Figure Set 20 shows that, in general, this variation is minimal. The C$_2$S observations have greater rms noise values, since C$_2$S was observed with a single beam rather than all seven beams in the KFPA. The HC$_3$N 22 – 21 data are noisier than the data of other lines observed with all KFPA beams, a systematic difference seen over all observations.

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Figure 4. Top: integrated intensity map of the NH$_3$ (1, 1) line for the B18 region. Contours are drawn at $[3, 6, 12, 24, \ldots]\sigma$, where $\sigma$ is the rms estimated from emission-free pixels. Beam size and scale bar are shown in the top left and bottom right corners, respectively. Bottom: the H$_2$ column density, $\log_{10}[N($H$_2)/$cm$^{-2}$], derived from SED fitting of Herschel submillimeter dust continuum data (A. Singh et al. 2017, in preparation). Purple contours show the NH$_3$(1, 1) integrated intensity, as in the top panel. White contours show the GAS map extent. Stars show the locations of Class 0/I and flat-spectrum protostars with a reliability grade of A- or higher (Rebull et al. 2010).
3. NH$_3$ Line Analysis

3.1. Line Fitting

We calculate the properties of the column of ammonia molecules using a forward-modeling approach in the pyspeckit package (Ginsburg & Mirocha 2011), which builds from the work of Rosolowsky et al. (2008) and Friesen et al. (2009) and relies on the theoretical framework laid out in Mangum & Shirley (2015). Under this approach, we consider a beam-filling slab of ammonia gas with a set of physical properties including para-ammonia column density ($N_pN_H_3$), kinetic temperature ($T_K$), velocity dispersion ($\sigma_v$), and line-of-sight velocity in the (kinematic) LSR (Local Standard of Rest) frame ($v_{LSR}$). While we observe the $(J, K) = (3, 3)$ line of ortho-ammonia, we do not directly incorporate any information from this line into our fit because of unknown ortho-to-para ratios that might differ from LTE (Local Thermodynamic Equilibrium; e.g., Faure et al. 2013).

Given a total column density for the molecule and a velocity dispersion for the slab, we use standard relations to determine the fraction of molecules found in each of the states, namely, the $(J,K)$ rotational states of the species and the upper ($u$, antisymmetric inversion symmetry) and lower ($l$, symmetric inversion symmetry) within those states. Our model incorporates three distinct temperatures. The kinetic temperature $T_K$ describes the velocity distributions of the particles in the system, notably of the collider species H$_2$ and He. The rotation temperature, $T_{rot}$, is the temperature that characterizes the rotational level population. Our work usually focuses on the temperature that defines the population ratio between the $(1, 1)$ and $(2, 2)$ states. Finally, $T_{ex}$ is the radiative excitation temperature of the observed spectral lines.

The NH$_3$ fitting usually proceeds under the assumption that the $(1, 1)$ and $(2, 2)$ lines have the same radiative excitation temperature and that the frequencies are approximately equal and $\leq kT_{ex}/h$. The former assumption is only approximately true: using RADEX (van der Tak et al. 2007) for $n = 10^4$ cm$^{-3}$, $T_K = 15$ K, and $N(NH_3) = 10^{14}$ cm$^{-2}$ gives $T_{ex}(1,1) = 8.5$ K and $T_{ex}(2,2) = 6.9$ K. Each of the inversion transitions consists of multiple resolved hyperfine components, and we further assume a constant $T_{ex}$ for all these transitions, which precludes our model representing hyperfine anomalies (e.g., Stutzki et al. 1984). We see, however, no evidence in our survey that these effects are important.

Our observations consist of antenna temperature as a function of frequency, so we generate a model of the spectral line given the input parameters ($N$, $T_K$, $T_{ex}$, $\sigma_v$, $v_{LSR}$). We assume that a single radiative excitation temperature, $T_{ex}$, characterizes both the $(1, 1)$ and the $(2, 2)$ transitions. We generate a model of optical depth as a function of frequency.

Figure 5. Same as Figure 4 but for NGC 1333. Stars show the locations of Class 0/I and flat-spectrum protostars (Dunham et al. 2015).
\( \tau(\nu) \) to produce a model spectrum of the main-beam radiation temperature (assuming the beam filling fraction = 1):

\[
T_{MB}(\nu) = [J(T_{ex}) - J(T_{bg})][1 - e^{-\tau(\nu)}].
\]

The optical depth, \( \tau(\nu) \), is a function of the input parameters. To derive \( \tau(\nu) \) from the input parameters, we first approximate the molecular population as having most of the p-NH\(_3\) in the (1, 1) and (2, 2) states so that we can define \( T_{rot} \) by the ratio of

Figure 6. Same as Figure 4 but for L1688. Stars show the locations of Class 0/I and flat-spectrum protostars (Dunham et al. 2015).
the column densities in the (2, 2) and (1, 1) states,

\[ N_{(2,2)} = N_{(1,1)} \frac{5}{3} \exp \left( -\frac{\Delta E}{k_{\text{rot}} T_k} \right), \]  

where \( \frac{5}{3} \) is the ratio of the rotational statistical weights of the states \((g_J = 2J + 1)\), and \( N(J, K) \) is the sum of the column densities of the two inversion levels. From here we find that \( T_{\text{rot}} \) can be related to the kinetic temperature by analytically solving the equations of detailed balance (Swift et al. 2005):

\[ T_{\text{rot}} = T_k \left[ 1 + \frac{T_k}{T_0} \ln \left[ 1 + \frac{3}{5} \exp \left( -\frac{15.7 \text{ K}}{T_k} \right) \right] \right]. \]  

Here, \( T_0 = 41.5 \text{ K} \) is the energy difference between the (2, 2) and the (1, 1) states. We then use this rotational temperature to calculate a partition function for the p-NH\(_3\) molecule, though the next metastable level is the (4, 4) line at 178 K above the ground state and is negligibly populated \((\tau < 1)\) for \( T_k < 65 \text{ K} \). The partition function is given by

\[ Z_{\text{para}} = \sum (2J + 1) \times \exp \left( -\frac{h (B_{\text{rot}} J (J + 1) + (C_{\text{rot}} - B_{\text{rot}}) J^2)}{K_{\text{B}} T_{\text{rot}}} \right). \]  

where \( B_{\text{rot}} \) and \( C_{\text{rot}} \) are the rotational constants of the ammonia molecule, 298117 and 186726 MHz, respectively (Pickett et al. 1998).

Since the excitation temperature defines the population ratio of the lower to the upper state, we can calculate \( N_l \) from the...
total column density in the (1, 1) state, \(N_{(1,1)}\),

\[
N_{(1,1)} = \frac{g_n}{g_l} \exp \left( \frac{-h\nu_0}{kT_{ex}} \right).
\]

so

\[
N_l = \frac{N_{(1,1)}}{1 + \frac{g_n}{g_l} \exp \left( \frac{-h\nu_0}{kT_{ex}} \right)}.
\]

Given the column density in the lower state, we then calculate a total integrated optical depth in the (1, 1) and (2, 2) lines using standard radiation relationships. In particular, the opacity per unit frequency,

\[
\alpha_{\nu} = \frac{c^2}{8\pi} \frac{1}{\nu_0^2} \frac{g_n}{g_l} n_A A_{ul} \left[ 1 - \exp \left( -\frac{h\nu_0}{kT_{ex}} \right) \right] \phi(\nu),
\]

where \(\nu_0\) is the line rest frequency, \(n_A\) is the volume density in the lower state of the transition, \(g_n\) and \(g_l\) are the statistical weights of the upper and lower states of a transition whose ratio is unity for each pair of inversion transitions, \(A_{ul}\) is the Einstein A coefficient, and \(\phi(\nu)\) is the line profile function defined such that

\[
\int \phi(\nu) d\nu = 1.
\]

We integrate over the line of sight and frequency to get the optical depth as a function of the column density in the lower transition of the spectral line,

\[
\tau = \int \alpha_{\nu} ds d\nu
= \frac{c^2}{8\pi} \frac{1}{\nu_0^2} \frac{g_n}{g_l} N_l A_{ul} \left[ 1 - \exp \left( -\frac{h\nu_0}{kT_{ex}} \right) \right],
\]

or, in terms of \(N_{(1,1)}\), which is the total column of molecules in the symmetric and antisymmetric (upper and lower) states of the \(J = 1, K = 1\) level,

\[
\tau_{(1,1)} = \int \alpha_{\nu} ds d\nu
= \frac{c^2}{8\pi} \frac{1}{\nu_0^2} \frac{g_n}{g_l} N_{(1,1)} A_{ul} \left[ 1 - \exp \left( -\frac{h\nu_0}{kT_{ex}} \right) \right].
\]

The optical depth for the (2, 2) transition has the same form. The column densities are related to the total column \(N\) through the partition function via \(T_{tot}\).

As per Mangum & Shirley (2015),

\[
A_{ul} = \frac{64 \pi^4 \nu_0^3}{3 \hbar c^3} \frac{1}{g_u} |\mu_{ul}|^2,
\]

where \(\mu_{ul}\) is the dipole moment of a given transition, which is related to the dipole moment of the molecule \(\mu^2\) by

\[
|\mu_{ul}|^2 = \frac{\mu^2}{J(J + 1)}.
\]

where \(\mu = 1.468 \times 10^{-18}\) esu cm for ammonia.

Finally, we calculate the line profile function \(\phi(\nu)\) from the hyperfine structure of the different transitions. Since each hyperfine transition is assumed to have the same radiative excitation temperature, \(\phi(\nu)\) is given as the weighted sum of the Gaussian line profiles:

\[
\phi(\nu) = \sum_i \frac{w_i}{\sqrt{2\pi} \sigma_{\nu,i}} \exp \left[ -\frac{(\nu - \nu_0 - \delta\nu_i)^2}{2\sigma_{\nu,i}^2} \right].
\]

The weights, \(w_i\), and frequency offsets from the rest frequency, \(\delta\nu_i\), are set by quantum mechanics and are tabulated in Mangum & Shirley (2015). The frequency widths of the lines...
are calculated in terms of the velocity widths from the Doppler formula: \( \sigma_v = (\nu_0 + \delta \nu) \sigma_c e^{-1} \).

This model provides a complete spectrum \( T_{MB} \) as a function of input parameters. We then use a nonlinear gradient descent algorithm (MPFIT; Markwardt 2009) implemented in Python to calculate the optimal values of the input parameters and their uncertainties (e.g., Press et al. 2002):

\[
\text{argmin} \chi^2 = \text{argmin} \frac{1}{\sigma^2(\nu_j)} \left[ \sum_j \left( T_{MB,obs}(\nu_j) - T_{MB}(\nu_j; N, T_K, T_{ex}, \sigma_c, v_{LSR}) \right)^2 \right].
\]

(15)

Nonlinear least-squares fitting can be unstable unless the algorithm is provided with a good set of initial conditions. In particular, the \( v_{LSR} \) value of the fit is critical, so we use guesses based on the velocity centroid of the line (or of the center hyperfine component for the ammonia lines). The velocity dispersion is initially taken to be the intensity-weighted second moment of the velocity around the centroid. We adopt \( \log_10(N/cm^2) = 14.5, T_K = 12 \) K, and \( T_{ex} = 3 \) K as our initial guesses. The fit is performed serially for each position in the map, starting from the pixel with the highest integrated intensity and working down in reverse order of integrated intensity. If a given position has a neighboring pixel with a good fit, the parameters of the successful fit are used as initial guesses for the next optimization.

In this release, we do not attempt to fit multiple velocity components or non-Gaussian velocity profiles to our spectra. Such approaches require human supervision under current implementations (Henshaw et al. 2016b). Our fits produce good-quality results for most of the studied regions (>95% of the detections in all regions released in DR1), but some lines of sight in NGC 1333, L1688, and Orion A show evidence for needing improved models for their underlying velocity components.

Recent work by Estalella (2017) presented the HFS hyperfine fitting tool. The assumptions embedded in our approach are essentially equivalent to those embedded in that tool, though Estalella (2017) used a relationship between \( T_{rot} \) and \( T_K \) based on the collision coefficients in Maret et al. (2009), which differs from the Swift et al. (2005) expression by >10% at \( T > 50 \) K. The optimization approach differs significantly, in that we use a
gradient descent nonlinear regression, whereas the HFS code uses a genetic algorithm. Our approach requires more accurate guesses for the initial conditions, but the strategy we have adopted leads to good convergence. The uncertainty estimates both follow standard estimates based on $\chi^2$ fitting.

### 3.2. The $v_{\text{LSR}}$-Tracked Integrated Intensity Maps

When calculating the integrated intensity map of a specific line, it is common practice to define a fixed velocity range that includes the emission of all hyperfine components for a single region. The maps presented here, however, cover large areas of individual star-forming clouds. In these regions, large velocity gradients make a fixed range suboptimal.

To create the NH$_3$ (1, 1) and (2, 2) integrated intensity maps, we therefore first produce a model emission cube given the best-fit models over the entire map. We set a threshold value $>0.0125$ K (i.e., slightly greater than machine precision) to identify the spectral channels with model line emission. We then select all the voxels (3D “pixels”) with brightness greater than the threshold to calculate the integrated intensity map. In regions where no line fit is found, we calculate the integrated intensity within a spectral window defined by the mean cloud $v_{\text{LSR}}$ and $\sigma_v$. We calculate the uncertainty at each pixel based on the channel range thus identified.

This method for calculating the integrated intensity while following the velocity gradients in a star-forming region depends on having a good model, which is usually the case for NH$_3$ emission in the clouds presented here. There are locations, however, where the emission is not perfectly fitted with a single component. In those cases, this method may not include some of the flux in the final moment maps. A detailed study of the gas kinematics will be done in future papers focusing on individual regions.

Since the spatial and kinematic distribution of NH$_3$ (3, 3) and the carbon-chain molecules does not typically follow that of NH$_3$ (1, 1) and (2, 2) and is significantly less extended, where detected, we use a single velocity range to produce integrated intensity maps of these transitions.

### 3.3. Data Masking

For all regions, the NH$_3$ (1, 1) and (2, 2) lines were fit where the NH$_3$ (1, 1) line had an S/N (signal-to-noise ratio) $> 3$ through the property map analysis described above. Here, $S/N = T_{\text{peak}}/\text{rms}$, where $T_{\text{peak}}$ is the peak brightness temperature in the NH$_3$ (1, 1) cube at a given pixel. At this S/N,
however, not all line parameters could be fit well over all pixels. We consequently mask the output parameter maps to remove poor fits to the NH$_3$ lines. Since $v_{\text{LSR}}$, $\sigma_v$, and $T_{\text{ex}}$ require good fits to the NH$_3$ (1, 1) line only, we mask pixels with an S/N $< 3$ in NH$_3$ (1, 1) integrated intensity. The parameters $T_K$ and $N$ require detections of the NH$_3$ (2, 2) line; for these property maps, we additionally mask any pixels with an S/N $< 3$ in the peak NH$_3$ (2, 2) line intensity. Finally, we apply a mask that removes any remaining isolated pixels that are unconnected with larger-scale features and are generally noisy data points. Additional masking based on the returned uncertainty in the fit parameters may be done for detailed analysis in future papers.

4. Results

4.1. The NH$_3$ Moment Maps

In Figures 4–7, we show the NH$_3$ (1, 1) integrated intensity maps of B18, NGC 1333, L1688, and Orion A (North). We further overlay the NH$_3$ (1, 1) integrated intensity contours on maps of the H$_2$ column density, $N$(H$_2$), in each region derived from spectral energy distribution (SED) modeling of continuum emission from dust observed with the Herschel Space Observatory (A. Singh et al., 2017, in preparation). The SED modeling is described in more detail in Section 4.3. The locations of Class 0/I and flat-spectrum protostars are highlighted based on infrared analysis of Taurus (Rebull et al. 2010), Perseus and Ophiuchus (Dunham et al. 2015), and Orion (Megeath et al. 2012).

In general, the NH$_3$ (1, 1) integrated intensity emission closely follows the H$_2$ column density as traced by dust continuum emission. The GAS data highlight individual cores and filamentary structure, as expected. However, at the achieved sensitivity level, they also reveal low-SNR emission that extends between the higher column density structures and follows, by visual inspection, the lower H$_2$ column density material. As an example, Figure 4 shows how NH$_3$ (1, 1) integrated intensity peaks highlight the dense cores in Taurus B18, while the extended emission matches the shape of the surrounding material seen in $N$(H$_2$). Toward L1688, the central, high column density cores are surrounded by material at lower $N$(H$_2$) values that fades away toward the northeast in Figure 6. Low-SNR NH$_3$ (1, 1) emission is similarly more extended in this direction. Extended low-SNR NH$_3$ emission can also be seen toward the more distant NGC 1333 and Orion A regions.

In Appendix B, we show the integrated intensity maps of NH$_3$ (2, 2) and NH$_3$ (3, 3) (where detected) toward the DR1 regions.

In appearance, the NH$_3$ (2, 2) integrated intensity maps closely match the NH$_3$ (1, 1) maps but with a lower SNR.
In NGC 1333, L1688, and Orion A, NH3 (3, 3) emission is detected, indicative of warmer dense gas present in these regions. In NGC 1333, the NH3 (3, 3) emission is compact and centered on two well-known sources, the bright Class 0/I object SVS 13 and the Herbig-Haro object HH12. In L1688, the NH3 (3, 3) emission is more diffuse, overlapping the NH3 (1, 1) contours in the northwest but primarily visible on the western edge. This region is an interface between the cold,
Figure 14. Same as Figure 11 but for Orion A (North).

Figure 15. $T_K$ (K) in B18, with the color scale chosen to match the spread in $T_K$ across all DR1 regions. Contours represent the NH$_3$ (1, 1) integrated intensity, as in Figure 4.
dense gas of the Ophiuchus A core and an edge-on photodissociation region associated with the B2V star HD 147889 (Loren & Wootten 1986; Liseau et al. 1999). The NH$_3$ (3, 3) emission in Orion A peaks at the BN/KL region and traces the associated filamentary structure extending north. The NH$_3$ (3, 3) emission is also prominent toward the Orion bar, highlighting this feature significantly better than NH$_3$ (1, 1).

4.2. Detections of Other Lines

In the previous sections, we focused primarily on emission from the NH$_3$ transitions toward the DR1 regions. We additionally mapped the rotational transitions of several carbon chains, which are listed in Table 2. Not all lines were detected in all regions, and the HC$_5$N transitions were not detected above the rms noise or in an integrated intensity map in any region. In Appendix C, we show the integrated intensity maps of the additional detected lines in each region. In Figure 8, we show the spectrum of each observed line averaged over each DR1 region after the masking of the edge pixels, as described in Section 2.5.

Toward B18, both HC$_3$N 9 – 8 and C$_2$S 2$_1$ – 1$_0$ are detected. For both molecules, the distribution of emission is significantly offset from NH$_3$ (1, 1), generally peaking away from the NH$_3$ emission peaks. While HC$_3$N is seen interior to some NH$_3$ (1, 1) contours, C$_2$S, where seen, appears to surround the NH$_3$ emission. Similar distributions of NH$_3$ and C$_2$S have been identified toward the L1495-B218 filaments in Taurus (Y. Seo et al. 2017, in preparation). This offset between emission from NH$_3$ and carbon-chain molecules is common in nearby star-forming regions and is generally explained by the depletion of C-bearing molecules onto dust grains at high densities while NH$_3$ remains in the gas phase. Asymmetric offsets like those seen in B18 might be indicative of the contraction of dense gas (Tafalla et al. 2004) or accretion of lower-density material onto the dense cores (Friesen et al. 2013).

HC$_3$N is also detected toward NGC 1333 in a single compact region (slightly greater in extent than the beam) located to the west of the central structure traced by NH$_3$ (1, 1). While C$_2$S is not visible in the integrated intensity map of NGC 1333 (not shown), the averaged C$_2$S spectrum in Figure 8 shows a significant detection. Similarly, C$_2$S is clearly detected toward L1688 in the averaged spectrum, while the integrated intensity map shows only a faint, S/N $\sim$ 3–4 feature near the map center. In future analysis, we will investigate extended, low-level emission of NH$_3$ and the other observed lines through spectral stacking techniques.

4.3. Relationship of NH$_3$ Emission to N(H$_2$)

4.3.1. Column Density of H$_2$

The H$_2$ column density, $N$(H$_2$), used here and in the maps above was determined in two steps (A. Singh et al. 2017, in preparation). First, the optical depth of the dust was obtained by fitting a modified blackbody to the SED of the thermal continuum emission from cold dust using Herschel maps at 160, 250, 350, and 500 µm. Second, this was converted to gas column density by a simple scale factor. An additional scale factor can be used to convert to $A_V$.

To implement the first step, we note that, for dust temperature $T_d$, the intensity of thermal dust emission is

$$I_{\nu} = (1 - e^{-\tau_{\nu}})B_{\nu}(T_d),$$

and we adopt $\tau_{\nu} = \tau_{\nu 0}(\nu/\nu_0)^{\beta}$. The dust opacity spectral index was taken to be $\beta = 1.62$, the mean value found by Planck over the entire sky (Planck Collaboration XI 2014). All maps were first convolved to the 36″ resolution of the 500 µm data and put on the same grid. Zero offsets were determined for each wavelength by comparison with Planck emission maps. Minor color corrections were applied during the SED fitting. The SED parameters $\tau_{\nu 0}$ and $T_d$ were determined at each pixel using $\chi^2$-squared minimization.

The required scale factor to convert to $N$(H$_2$) can be seen via the relation

$$\tau_{\nu 0} = \kappa_{\nu 0} \mu m_{H} N(H_2),$$

where $\mu = 2.8$, $m_{H}$ is the mass of a hydrogen atom, and $\kappa_{\nu 0}$ is the opacity (incorporating a gas-to-dust mass ratio of 100), which is taken to be 0.1 cm$^2$ g$^{-1}$ at $\nu_0 = 1000$ GHz (Hildebrand 1983). The considerable systematic uncertainty in the opacity propagates uniformly throughout the map into a systematic uncertainty in the scale of $N$(H$_2$).

Ideally, one could scale the dust-based $\tau_{\nu 0}$ directly into $A_V$, which is also proportional to dust column density. This scaling, too, is uncertain (Planck Collaboration XI 2014). Here, we simply use $N$(H$_2$) = 9.4 $\times$ 10$^{20}$ cm$^{-2}$ ($A_V$ mag$^{-1}$), which is based on data for the diffuse interstellar medium, not molecular
clouds; thus, the two-figure precision given belies the actual uncertainty.

Regional variations in dust spectral properties could impact the values determined through SED modeling (and thus the threshold for NH$_3$ emission discussed below), although this is likely a small effect compared to the uncertainty in the scaling: for example, a change in $\beta$ of 0.05 produces a change in $N$(H$_2$) of only $\sim$5%.

4.3.2. The N(H$_2$) Threshold for NH$_3$ Emission

Figure 9 (top) shows a smooth increase in the fraction of pixels with NH$_3$ emission as $N$(H$_2$) increases, with some variation between regions in the rate of rise in the correlation and in the H$_2$ column density, where NH$_3$ is found universally. The survey initially targeted regions with extinctions $A_V > 7$, based on previous observations of NH$_3$ in nearby star-forming regions. That this was a good choice is confirmed by the DR1 data, where, above this extinction value (highlighted by the dashed gray line in the figure, assuming $N$(H$_2$) = $9.4 \times 10^{20}$ cm$^{-2}$ (A$_V$ mag$^{-1}$)), $\geq$60% of the pixels have detectable NH$_3$ emission above the survey noise levels in all DR1 regions. The exception is B18, where the threshold appears to be slightly higher. Furthermore, the survey footprints were rectangular and did not follow the high column density contours precisely; thus, lines of sight corresponding to lower column densities were surveyed too.

4.3.3. Comparison to Simulations

We compared the GAS data to results calculated from a synthetic observation of NH$_3$ emission produced by a 3D hydrodynamic simulation. The simulated emission map is based on astrochemical modeling performed by Offner et al. (2014). The abundances were computed by post-processing the simulation with 3D-PDR, a 3D photodissociation region code (Bisbas et al. 2012), assuming the simulation is irradiated with a uniform 1 Draine field. We next computed the emission using RADMC-3D (Dullemond et al. 2012). Finally, to model the instrumental effects, we convolved the emission map with a 32" beam for a distance of 250 pc and added Gaussian noise with $\sigma_{\text{rms}} = 0.15$ K km s$^{-1}$, a typical value from the GAS NH$_3$ (1, 1) integrated intensity maps.

Figure 9 (middle) shows the emission fraction for the total simulation domain ($n_H = 900$ cm$^{-3}$) and two subregions ($n_H = 1700$ and $n_H = 830$ cm$^{-3}$). These distributions agree well with the GAS distributions and demonstrate that variation in the underlying gas densities can account for some of the spread between regions. Differences between regions may also result from variations in the local UV radiation field and mean column density, which we will explore in future work.

Lastly, Figure 9 (bottom) shows the cumulative distribution of $N$(H$_2$) in the observed footprints of the GAS DR1 regions. A more gradual increase is seen relative to the top panel, where the presence of NH$_3$ rises steeply above $\log_{10} N$(H$_2$)/[cm$^{-2}$] $\sim$ 21.5.

Figure 9 shows that observations of NH$_3$ inversion transitions become an excellent indicator of where there is gas at higher column densities—and thus probably higher volume densities—but miss material at lower column densities that can be detected via the thermal dust continuum emission.
The ability of NH$_3$ to highlight higher-density structures enables analyses of structure sizes, masses, and concentrations that are complementary to similar analyses using dust continuum emission. For example, we noted previously that filaments are prevalent within star-forming regions, with a filamentary width of $\sim$0.1 pc suggested by profile fitting of the mid- and far-infrared dust emission (Arzoumanian et al. 2011). The authors define the filament “width” as the FWHM of a Gaussian fit to the innermost section of the filament’s radial profile. In Figure 10, we show a filament in NGC 1333 in (a) NH$_3$ (1, 1) integrated intensity and (b) $N$(H$_2$). In panels (c) and (d), we show the filament radial profile in NH$_3$ and $N$(H$_2$), respectively, averaged along the long axis shown by the black line in panels (a) and (b). We then fit a Gaussian plus constant offset to the innermost 0.1 pc of each radial profile, matching the analysis of Arzoumanian et al., with the results shown in red. Similar to the result of Arzoumanian et al., we find a filament FWHM of 0.086 pc in $N$(H$_2$) but show that the filament is narrower in NH$_3$ emission by a factor of $\sim$1.4.

Locating the range of $N$(H$_2$) values from panel (d) of Figure 10 in the top panel of Figure 9 shows that the NH$_3$ emission does not measure the full column density—only the denser core. Furthermore, in $N$(H$_2$), the filament is embedded within lower column density material and crossed by additional narrow features, while the NH$_3$ emission highlights the filament only.

Future work using the GAS data set will identify filamentary structures systematically using algorithms such as filfinder (Koch & Rosolowsky 2015) and DisPerSE (Sousbie 2011). This will probe the properties of filamentary structures at different spatial scales and determine what dominates the kinematics within the filamentary structures at each scale, thus providing insight into their origin.

### 4.4. Property Maps

We present the property maps resulting from the NH$_3$ line fitting described in Section 3. In Figures 11–14, we show maps of $v_{\text{LSR}}$ and $\sigma_v$ for each of the DR1 regions. The gas temperature $T_K$ is presented for all regions in Figures 15–18. Maps of the NH$_3$ column density, $N$(NH$_3$), are shown for all regions in Appendix D.

While detailed analyses of the dense gas properties traced by NH$_3$ in the Gould Belt will be presented in future papers, we discuss here some general results and trends in the data.

Figures 11–14 show significant variations in the kinematic properties traced by NH$_3$ between the DR1 regions. In both B18 and L1688, gas velocities are concentrated around the mean cloud value with only a small spread. In B18, at the survey sensitivity, we detect NH$_3$ toward only a small fraction of the extended gas surrounding the NH$_3$ peaks, and the $v_{\text{LSR}}$ values shown represent mainly the $v_{\text{LSR}}$ of the densest NH$_3$ structures in the region. In the other DR1 regions, we detect more of the extended NH$_3$ emission. The $v_{\text{LSR}}$ map of L1688 in Figure 13 shows that distinct variations in $v_{\text{LSR}}$ are seen between some of the NH$_3$ structures and the surrounding dense gas, but the velocity changes are small ($\lesssim$1 km s$^{-1}$). Toward NGC 1333, a broader distribution in $v_{\text{LSR}}$ is visible in Figure 12. Unlike the variation in $v_{\text{LSR}}$ between compact and extended emission in L1688, gradients in $v_{\text{LSR}}$ are seen along the filamentary structures in NGC 1333. A large gradient in $v_{\text{LSR}}$ is also clearly visible extending along the Orion A filament from north to south, with a smaller velocity gradient perpendicular to the filament in the south.

In Figure 19, we show the distributions of $\sigma_v$, $T_K$, $N$(NH$_3$), and $\chi(N$(H$_2$)) over the DR1 regions. For each parameter, we show the probability density function normalized such that the integral over the range is 1 for each region. We include only those pixels with small uncertainties in the fitted values, as described in the figure captions.

Figure 19(a) reveals a systematic increase in the spread of the NH$_3$ velocity dispersion in the DR1 regions that reflects the increase in the level of star formation activity from the least active region, B18, to the most active region, Orion A. In
B18, NGC 1333, and L1688, the \( \sigma_v \) distribution shows a narrow peak at small velocity dispersions and a “tail” of greater velocity dispersions that increases in both the distribution amplitude relative to the narrow \( \sigma_v \) peak and the maximum \( \sigma_v \) present in the region. In Orion A, the narrow peak might still exist, but the population of larger \( \sigma_v \) values is substantially greater. The lower limit of measured \( \sigma_v \) in all regions is greater than the velocity resolution of the NH\(_3\).
Similar to the distributions of \( \sigma_r \), both the mean gas kinetic temperature and the spread of temperatures measured varies systematically between the DR1 regions with increasing star formation activity. Figure 19(b) shows that B18 contains the coldest dense gas of the DR1 regions, with a mean \( T_k \lesssim 10 \) K and only a small variation about that value. In both NGC 1333 and L1688, a moderate fraction of the dense gas is similarly cold (\( T_k \sim 10 \) K) but with an increasing spread to higher temperatures. Previous pointed NH3 observations of dense cores in Perseus found a typical temperature of 11 K for these objects, in agreement with our data (Rosolowsky et al. 2008), whereas in NGC 1333 the warm gas is concentrated around known YSOs. In L1688, dense gas is more likely to be \(~14–15\) K, as seen previously in smaller NH3 maps of some of the cores in this region (Friesen et al. 2009). Toward Orion A, only a small fraction of the dense gas is as cold as 10 K, with typical temperatures \( T_k \sim 15–20\) K, up to very large values near the Orion KL region (seen in Figure 18). At these temperatures (>30 K), we expect significant populations of higher-order NH3 (J, K) levels, and our temperature estimates from the (1, 1) and (2, 2) lines become inaccurate.

Figure 19(c) shows the distribution of NH3 column densities over the DR1 regions. For all regions, we find a similar increase in \( N(p\text{-NH}_3) \) at low column densities and a similar peak at \( \log N(p\text{-NH}_3) \sim 14 \). B18 shows a relatively sharp cutoff in the maximum column density present. However, \( N(p\text{-NH}_3) \) extends to higher values in the other regions, with the largest column densities found in Orion A.

The resulting distributions of NH3 abundances, \( X(\text{NH}_3) = N(\text{NH}_3)/N(H_2) \), shown in Figure 19(d) have very similar peak values of \( \log X(\text{NH}_3) \sim -8.5 \) to \(-8.0 \). A tail to very high NH3 abundances is seen in Orion A but might result from difficulties in accurately fitting the submillimeter continuum SED in this active region. In NGC 1333, the abundance distribution appears bimodal. We will present more detailed analysis of the dust properties and NH3 abundance distributions in an upcoming paper.

5. Summary

We present data from the first release (DR1) for GAS, including cubes, moment maps, and property maps, toward B18 in Taurus, L1688 in Ophiuchus, NGC 1333 in Perseus, and Orion A North in the Orion molecular cloud. We furthermore describe in detail the DR1 calibration, imaging, and line-fitting pipelines. The four Gould Belt clouds observed span a range of \( H_2 \) column density and star formation activity. The extensive and sensitive NH3, HC2N, HC3N, and C2S observations of these regions greatly increase the total contiguous areal coverage of dense molecular gas tracers in these well-studied star-forming regions.

All cubes and maps are publicly available through https://dataverse.harvard.edu/dataverse/GAS_DR1, as are the imaging and analysis pipelines.

Some highlights from the sensitive GAS data are as follows.

1. Extended NH3 (1, 1) emission is detected toward all DR1 regions, revealing the physical properties of both the dense gas associated with prestellar and star-forming cores and filaments and their moderately dense molecular envelopes.
2. The NH3 (1, 1) emission is a particularly good tracer of material at higher \( N(H_2) \), tracking the \( H_2 \) column density as traced by dust continuum emission well. In three of the four DR1 regions, NH3 is present above our map rms noise levels in \(~60\%\) of the pixels at \( N(H_2) \geq 6 \times 10^{21} \text{cm}^{-2} \), or \( A_V \geq 7 \).
3. We observe some variation between the regions in the fraction of pixels with NH3 as \( H_2 \) column density increases. We compare the GAS data to results calculated from a synthetic observation of NH3 emission produced by a 3D hydrodynamic simulation. The simulated distributions agree well with the GAS distributions and demonstrate that variation in the underlying gas densities can account for some of the spread between regions. Differences between regions may also result from variations in the local UV radiation field and mean column density, which we will explore in future work.
4. Previously unmapped NH3 (3, 3) emission is detected toward NGC 1333, L1688, and Orion A. Highlighting warmer, dense gas, NH3 (3, 3) emission is coincident with YSOs and photodissociation region edges.
5. The carbon-chain molecules C2S and HC5N are strongly detected toward B18 but are faint or undetected in the integrated intensity maps of the other DR1 regions. In Taurus, the spatial distributions of C2S and HC5N are offset from the NH3 emission. We detect C2S toward NGC 1333 and L1688 only in spectra that were averaged over the entire observation extent. The observed HC5N lines are not detected toward any DR1 target.
6. The distributions of gas temperature and velocity dispersion from the NH3 line vary systematically between DR1 regions, in step with increasing star formation activity. Lower \( T_k \) is found overall in B18, increases in NGC 1333 and L1688, and is greatest in Orion A. Similarly, \( \sigma_v \) reaches greater values in L1688 and Orion A relative to B18 and NGC 1333.

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Facility: GBT (KFPA+VEGAS).
Software: 3d-pdr (Bisbas et al. 2012), Astropy (Robitaille et al. 2013), GTBIDL (Morganian et al. 2006), GBT KFPA data reduction pipeline (Masters et al. 2011), Matplotlib (Hunter 2007), MPFIT (Markwardt 2009), pyspeckit (Ginsburg & Mirocha 2011), RADMC-3D (Dullemond et al. 2012; Goodman 2012; Beaumont et al. 2015).

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20 In most works, the total column density of NH3 (including ortho and para states) is reported, \( N(\text{NH}_3) \). A simple way to estimate the total column density of NH3 is \( N(\text{NH}_3) \approx 2 \times N(p\text{-NH}_3) \), if the ortho-to-para ratio is the LTE value of 1.
Appendix A
Maps of the rms Noise in the NH₃ (1, 1) Observations for All DR1 Regions

The rms noise maps of the NH₃(1,1) line, for all regions, are shown in Figure 20.

Figure 20. rms noise (K) over the NH₃ (1, 1) map toward B18. Scale bar is at lower right. (The complete figure set (4 images) is available.)

Appendix B
The NH₃ (2, 2) and (3, 3) Integrated Intensity Maps, Where Detected

The integrated intensity maps of the NH₃ (2, 2) line for all regions are shown in Figure 21.
The integrated intensity maps of the NH₃ (3, 3) line for NGC1333, L1688, and OrionA are shown in Figure 22.

Figure 21. Integrated intensity of NH₃ (2, 2) toward B18. Contours show the NH₃ (1, 1) integrated intensity, as in Figure 4. Beam size and scale bar are at upper left and lower right, respectively. (The complete figure set (4 images) is available.)
Appendix C
The HC$_5$N 9 − 8 and C$_2$S 2$_1$ − 1$_0$ Integrated Intensity Maps, Where Detected

The integrated intensity maps of the HC$_5$N and C$_2$S lines for B18 are shown in Figure 23 and 24, respectively.

**Figure 22.** NH$_3$ (3, 3) integrated intensity toward NGC 1333. Contours show the NH$_3$ (1, 1) integrated intensity, as in Figure 4. The locations of the Class 0/I object SVS 13 and the Herbig-Haro object HH12 are identified by the upward- and downward-facing triangles, respectively.

(The complete figure set (3 images) is available.)

**Figure 23.** HC$_5$N 9 − 8 integrated intensity in B18. Contours represent the NH$_3$ (1, 1) integrated intensity, as in Figure 4.
The integrated intensity maps of the HC$_5$N line for NGC1333 and L1688 are shown in Figure 25 and 26, respectively.

Appendix D

The NH$_3$ Column Density Maps for All DR1 Regions

The NH$_3$ column density maps for B18, NGC133, L1688, and OrionA are shown in Figures 27, 28, 29, and 30, respectively.
Figure 27. $N(\text{NH}_3)$ (cm$^{-2}$) in B18. Contours represent the NH$_3$ (1, 1) integrated intensity, as in Figure 4.

Figure 28. Same as Figure 27 but for NGC 1333.
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Figure 29. Same as Figure 27 but for L1688.

Figure 30. Same as Figure 27 but for Orion A (North).
