THE MILLIMETER ASTRONOMY LEGACY TEAM 90 GHz (MALT90) PILOT SURVEY

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ABSTRACT

We describe a pilot survey conducted with the Mopra 22 m radio telescope in preparation for the Millimeter Astronomy Legacy Team Survey at 90 GHz (MALT90). We identified 182 candidate dense molecular clumps using six different selection criteria and mapped each source simultaneously in 16 different lines near 90 GHz. We present a summary of the data and describe how the results of the pilot survey shaped the design of the larger MALT90 survey. We motivate our selection of target sources for the main survey based on the pilot detection rates and demonstrate the value of mapping in multiple lines simultaneously at high spectral resolution.

Key words: ISM: molecules – stars: formation – stars: massive – surveys

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1. INTRODUCTION

The goal of the Millimeter Astronomy Legacy Team Survey at 90 GHz (MALT90) is to characterize the physical and chemical conditions of dense molecular clumps associated with high-mass star formation over a wide range of evolutionary states. MALT90 will do this by taking advantage of the newly upgraded Mopra Spectrometer (MOPS¹¹) and the on-the-fly (OTF) mapping capability of the Mopra 22 m radio telescope. The survey will obtain molecular line maps of 3000 candidate dense molecular clumps. The clumps will be selected so as to cover a broad range of evolutionary states, from pre-stellar clumps to accreting high-mass protostars and on to H ii regions. The survey will be conducted at 90 GHz because this frequency regime contains numerous molecular lines which have typical critical densities for collisional excitation of $\gtrsim 10^5$ cm$^{-3}$ and are therefore excellent tracers of dense gas. Such data will allow us to study the Galactic distribution of these clumps, their physical properties, and their chemical variation and evolution; this basic information is necessary to constrain theories of high-mass star formation. In addition, MALT90 will provide a valuable database of dense molecular clumps associated with high-mass star formation for future ALMA observations.

MALT90 will map roughly 3000 dense molecular clumps, providing an order of magnitude more sources than previous comparable surveys (e.g., Shirley et al. 2003; Pirogov et al. 2003; Gibson et al. 2009; Wu et al. 2010). A large number of sources will allow us to divide the sample into sub-samples (based on mass, evolutionary phase, etc.) yet retain a sufficient number of sources in each sub-sample for statistical analysis. Because dense molecular gas occupies only a small solid angle of the Galactic plane and molecular emission at 90 GHz is relatively faint, a blind fully sampled 90 GHz survey of a significant portion of the Galactic plane is impractical. Instead, we must choose targets based on other methods for identifying dense molecular clumps. The main purpose of the MALT90 pilot survey described herein is to choose the best method for identifying dense molecular clumps, with the twin aims of having a high percentage of detections within our sensitivity limits and covering a broad range of evolutionary states.

Throughout this paper, we will use the term “dense molecular clump” to refer to our sources. The choice of “clump” follows the naming system used by Williams et al. (2000) and Bergin & Tafalla (2007) which distinguishes between molecular clouds, clumps, and cores. In this scheme, clumps are coherent regions in position-velocity space with typical masses of 50–500 $M_\odot$, typical sizes of 0.3–3 pc, and typical mean densities of $10^3$–$10^4$ cm$^{-3}$ which may contain additional substructures called cores that give rise to individual stars or stellar systems. Our goal in MALT90 is to identify and map the clumps that give rise to a cluster of stars containing one or more high-mass stars.

This paper will focus predominantly on the technical validation of the survey and explain the design choices motivated by the pilot survey. Data from the pilot survey will be combined with the full MALT90 survey data (where the diverse selection criteria in the pilot survey are not detrimental to statistical
analysis) for the specific scientific projects in MALT90. These analyses will appear in future papers.

2. TARGET SELECTION

We used six different input catalogs for selecting sources; three were lists that we produced for our pilot survey and three were based on pre-existing catalogs. From these lists we chose 20–40 sources near integer Galactic longitudes covering the range of longitudes accessible from Mopra. This assured a random selection of sources from the three pre-compiled lists and allowed us to focus on a limited portion of the sky when developing our own lists, while still covering a broad range of Galactic longitudes. The six selection criteria are summarized in Table 1.

The first three lists were produced for our pilot survey. For these lists we chose sources based on the mid-infrared morphology of candidate dense molecular clumps as revealed by two Spitzer Space Telescope Legacy surveys: the Galactic Legacy Infrared Mid-Plane Survey Extraordinaire (GLIMPSE; Benjamin et al. 2003) and the 24 and 70 Micron Survey of the Inner Galactic Disk with MIPS (MIPSGAL; Carey et al. 2009). GLIMPSE covers the Galactic plane in the Infrared Array Camera (IRAC; Fazio et al. 2004) bands from 3.6 to 8.0 μm, while MIPSGAL covers much the same area at 24 and 70 μm using the Multiband Infrared Photometer for Spitzer (MIPS; Rieke et al. 2004).

We examined the GLIMPSE and MIPSGAL mosaics using three criteria designed to select sources in distinct evolutionary states as shown in Figure 1. A preliminary version of the Peretto & Fuller (2009) catalog of Infrared Dark Clouds (IRDCs) was used to identify 8 μm extinction features near integer Galactic longitudes. This catalog was then trimmed to remove any sources which contained a 24 μm point source (since this is most likely a protostar). We refer to this the GLIMPSE-Dark catalog, and these sources should correspond to the earliest phase of high-mass star formation. We then examined the Spitzer mosaics near integer Galactic longitudes by hand to choose candidate dense molecular clumps containing either 24 μm point sources or bright extended 8 μm emission. If a clump of 8 μm dark extinction was coincident with a 24 μm point source, we assigned it to the MIPSGAL catalog and classified this candidate clump as protostellar. In the case of bright extended emission at 8 μm we assigned the source to the GLIMPSE-Bright catalog and classified it as an H ii region.

The correspondence between the appearance of a source in the Spitzer surveys and its evolutionary state is clearly imperfect. The projection of unrelated objects along a given line of sight, inhomogeneities in the diffuse 8 μm emission, and sensitivity limits (e.g., our ability to detect 24 μm point sources will depend on intrinsic luminosity and distance) are three possible sources of misidentification. However, this system provides a quick and uniform way to make an initial assessment of a candidate dense molecular clump’s evolutionary state.

The other three lists in our pilot survey were produced using pre-existing catalogs. The first came from the H2O Southern Galactic Plane Survey (HOPS; Walsh et al. 2008) which used Mopra at 1.2 cm to map the Galactic plane from −70° < l < 30° in NH3 and H2O. Because the HOPS NH3 (1,1) and (2,2) lines have a similar critical density (n ~ 10^4 cm^{-3}) as the MALT90 90 GHz lines (n ~ 10^5 cm^{-3}), bright NH3 sources in HOPS are likely to be detected by Mopra in the 90 GHz lines. The last two catalogs came from millimeter/submillimeter continuum surveys which reveal the location of regions with high dust column density, typically corresponding to dense molecular clumps. The Beltrán et al. (2006) survey at 1.2 mm made maps

| Data             | Criterion           | Object Identified                      | Shorthand          |
|------------------|---------------------|----------------------------------------|--------------------|
| GLIMPSE 3.6 to 8 μm | Dark extinction     | Pre-stellar (IRDC) clump               | GLIMPSE-dark       |
| GLIMPSE 8 μm     | Extended emission   | H ii region                             | GLIMPSE-bright     |
| MIPSGAL 24 μm    | Point source        | Accreting protostar                    | MIPSGAL            |
| HOPS a 1.2 cm    | Compact NH3 source  | Dense clump                             | HOPS               |
| IRAS + 1.2 mm emission | IRAS + mm continuum | Star-forming dense clump                | IRAS               |
| ATLASGAL c 870 μm | Compact continuum   | Dense clump                             | ATLASGAL           |

Notes.

a Walsh et al. (2008).
b Beltrán et al. (2006).
c Schuller et al. (2009).
around *Infrared Astronomical Satellite* (IRAS) point sources using the Swedish-ESO SubMillimeter Telescope (SEST) and the SEST Imaging Bolometer Array (SIMBA). Because the Beltrán et al. (2006) maps were made toward IRAS point sources, these sources are likely to contain a protostar or H II region, which gives rise to the IRAS emission; we shall refer to this catalog as the IRAS catalog for convenience. Finally, the APEX (Atacama Pathfinder Experiment) Telescope Large Area Survey of the Galaxy (ATLASGAL; Schuller et al. 2009) is a survey of the Galactic plane (±60° in longitude over ±1°5 in latitude and −80° ≤ l ≤ −60° with −2° ≤ b ≤ 1°) at 870 μm. From a preliminary compact source catalog we chose ATLASGAL sources with peak fluxes above 2 Jy beam−1 closest to integer Galactic longitudes.

In two cases (G336.994−00.019 and G339.968−00.529), a candidate dense molecular clump was chosen independently from two different catalogs. We consider these sources to belong to both catalogs when considering detection statistics.

In summary, we have combined six separate lists, four of which we expected to select particular evolutionary states (the *Spitzer*-identified sources and the Beltrán et al. (2006) catalog of IRAS sources), and two of which (ATLASGAL and HOPS) we expected to be less biased with respect to evolutionary status. For both ATLASGAL and HOPS, the most luminous sources will tend to be the hottest, more evolved sources. To select a broad range of evolutionary states from these surveys it is necessary to include some additional information as we discuss in Section 5.2.

### 3. DATA

We carried out observations for the MALT90 pilot survey in the austral winter of 2009 from June 15 to 24, the OTF mapping mode of Mopra. Maps were made with the beam center running on a 3.4′ × 3.4′ grid. At typical distances to high-mass star-forming regions (several kpc) this map size is sufficient to cover the expected spatial extent of a few parsecs for our dense molecular clumps. The scan rate was 3′92 s−1. The map is made with 12″ spacing between the rows, giving 17 rows per map. Since the Mopra beam at 90 GHz is 36″, this row spacing provides redundancy in the map. OFF positions were chosen at ±1 deg in Galactic latitude away from the plane (positive offset for sources at positive Galactic latitude and vice versa), and though the OFF positions were not explicitly checked for line emission, no map showed evidence of contamination from signal in the OFF. A single OFF position was observed for every two scan rows. In general, maps were made by scanning in strips of constant Galactic longitude, although for two sources maps were also taken by scanning in strips of constant Galactic latitude, although for two sources

| IF | Species | $J$ | $T_{\text{sys}}$ (GHz) | Primary Information Provided |
|---|---|---|---|---|
| 1 | N$_2$H$^+$ | 1–0 | 93.173772 | High column density, depletion resistant, optical depth |
| 2 | $^{13}$CS | 2–1 | 92.494303 | High column density |
| 3 | H | 41υ | 92.034475 | Ionized gas |
| 4 | CH$_3$CN | $J_K = 5_1–4_1$ | 90.979020 | Hot core |
| 5 | HC$_5$N | $J = 10–9$ | 91.199796 | Hot core |
| 6 | $^{13}$C$^{15}$S | $J = 2–1$ | 90.926036 | High column density |
| 7 | HNC | $J = 1–0$ | 90.663572 | High column density, cold gas |
| 8 | HC$_3^{13}$CN | $J = 10–9$, $F = 9–8$ | 90.593059 | Hot core |
| 9 | HCO$^+$ | $J = 1–0$ | 89.188526 | High column density, kinematics |
| 10 | HCN | $J = 1–0$ | 88.631847 | High column density, optical depth |
| 11 | HNCO | $J_{K_a,K_b} = 4_{0,4}–3_{0,3}$ | 88.239027 | Hot core |
| 12 | HNCO | $J_{K_a,K_b} = 4_{1,3}–3_{1,2}$ | 87.925238 | Hot core |
| 13 | C$_2$H | $N = 1–0$, $J = 3/2–1/2$, $F = 2–1$ | 87.316925 | Photodissociation region |
| 14 | SiO | $J = 2–1$ | 86.847010 | Shock/outflow |
| 15 | H$^{13}$CO$^+$ | $J = 1–0$ | 86.754330 | High column density, optical depth |
| 16 | H$^{13}$CN | $J = 1–0$ | 86.340167 | High column density, optical depth |

Note. Frequencies listed above are the rest frequencies used in converting to velocity scale (FITS keyword RESTFREQ).
protostars once molecules have been liberated off dust grains by radiation or shocks. Three more lines trace particular environments: the recombination line H41α traces ionized gas (Shukla et al. 2004); SiO (2–1) is seen when SiO is formed from shocked dust grains, typically in outflows (Schilke et al. 1997); and C2H is produced in photodissociation regions (e.g., Lo et al. 2009; Gerin et al. 2011), where the $N = 1–0, J = 3/2–1/2, F = 2–1$ transition is the strongest of several C2H lines in this spectral window. Henceforth we will refer to these transition lines by the molecule name where this usage is unambiguous (i.e., HCO* instead of HCO* (1–0)).

The maps were reduced using the LIVEDATA and GRIDZILLA packages.13 LIVEDATA performs bandpass calibration using reference OFF scans and fits a second-order polynomial to the data points: the recombination line H41α (Walsh et al. 2008) pipeline, and (3) moment maps. Although Gaussian fitting is critical for certain measurements (particularly for lines with hyperfine component), moment maps are a fast and relatively robust way to measure basic line properties and this study will focus only on properties well measured by moment analysis. The results of the “by-hand” examination were used to select the parameters used in generating moment maps.

As a first step to making moment maps, we calculated an error map for each spatial pixel by computing the standard deviation of the spectra at that position using $3\sigma$ iterative rejection. In this way, we remove strong line features from the calculation and derive an estimate of the per-channel noise in the spectrum at each point in the map. Our OTF maps have less integration time at the edges, so a spatial error map is required in order to properly assess features near the noisy edges of the map.

Zeroth ($M_0$; integrated intensity), first ($M_1$; central velocity), and second ($M_2$; line width) moment maps were made according to

$$M_0 = \int I(v) \, dv,$$

$$M_1 = \frac{1}{M_0} \int I(v) v \, dv,$$

$$M_2 = \sqrt{\frac{1}{M_0} \int (I(v) - M_1)^2 \, dv},$$

where $I(v)$ is the intensity at a given frequency, $v$. The error on the zeroth moment is simply

$$\sigma_{M_0} = \sigma \sqrt{n},$$

where $\sigma$ is the per-channel noise in the spectrum as calculated for our error map and $n$ is the number of spectral channels used. Errors on the first and second moments ($\sigma_{M_1}$ and $\sigma_{M_2}$) are calculated from propagation of uncertainty on the formulae for $M_1$ and $M_2$ above, but are omitted for space.

The main choice in making moment maps lies in identifying the region of the cube to use. For the pilot survey, automatic line detection was hindered by baseline ripples (particularly in worse weather) and noisy edges on the bandpasses. Improvements to the data processing pipeline are expected to mitigate baseline ripples for the full MALT90 survey and allow for automatic detection of lines, but these were not available for processing the pilot data. Therefore, we use hand-identified velocities for each source to make moment maps in fixed-width windows around these velocities. Hand-identified velocities were estimated by recording the velocity at the center of each line as estimated by eye and averaging the velocities from whichever of the four main lines ($N_2H^+$, HNC, HCO+, HCN) were clearly detected above the noise. Where no line could be identified (53 sources), no moment map was made.

Two different velocity ranges were used for making moment maps: a narrow range for detection and a broader range for measuring line properties. A narrow velocity range ($\pm 2.25$ km s$^{-1}$) produced the highest signal-to-noise measurement for weak, narrow lines by limiting the spectral region considered to the peak of the line. Typical FWHM line widths ($\Delta V_{\text{FWHM}}$) for our sources are between 5 and 8 km s$^{-1}$ (as measured in HNC; see Section 5.1), so this narrow velocity range does not adequately measure line properties. Therefore, a broader velocity range ($\pm 8.25$ km s$^{-1}$) was also used to make moment maps. This range typically covers most of the line down to the noise, and thus comes much closer to estimating the true moments of the line. In addition, it includes the hyperfine components in both the N2H$^+$ and HCN lines, providing a better measure of the integrated intensity for those lines; the trade-off is higher noise.

We therefore report detections from the narrow velocity integration range ($\pm 2.25$ km s$^{-1}$) and report moment information from the broader range ($\pm 8.25$ km s$^{-1}$).

Integrated intensity ($M_0$) maps for each source detected in any line are presented in Figure 2. To facilitate inter-comparison, all maps are displayed on the same intensity scale, with the lowest contour at 1 K km s$^{-1}$, which is a typical $5\sigma$ uncertainty in the integrated intensity. These moment maps are all made in a fixed velocity range around hand-identified central velocities. We show the spectra for our four main lines at their respective positions of maximum integrated intensity in Figure 3. For sources without any detections, Figure 3 shows the spectra at the center of the map.

Basic source properties, including our hand-determined centroid velocities and the per-channel standard deviation at the center of the map (which is representative of the fully sampled portion of the map), are summarized in Table 3. In five cases, two distinct and widely separated velocity components were seen in a source. In these cases, each velocity component was used to create moment maps. The stronger line is listed first in Table 3 and is the main line used when considering detection statistics. We did not consider these as separate sources for the detection statistics (because we are interested in knowing if a given catalog will give us a detection at a given spatial position),
Figure 2. Example integrated intensity (zeroth moment; \( M_0 \)) map of G263.620−00.530. A uniform color scale is used in all figures in this figure set, starting at 1 K km s\(^{-1}\), which is a typical 5\( \sigma_{M_0} \) contour for our data set. Maps taken in worse weather have higher noise and the edges of the maps have higher noise, so not all emission at this level is necessarily significant. We use spatially varying noise maps to identify genuinely significant emission for the analysis presented in the text. (The complete figure set (134 images) is available in the online journal.)

Table 3

| Name               | Glon (deg) | Glat (deg) | R.A. J2000 (HH:MM:SS) | Decl. J2000 (DD:MM:SS) | Catalog               | Velocity LSR (km s\(^{-1}\)) | \( T_{\text{rms}} \) (K) |
|--------------------|------------|------------|-----------------------|------------------------|-------------------------|-------------------------------|-----------------------------|
| G263.620−00.530    | 263.620    | −0.530     | 08:45:36.003          | −43:51:01.99           | IRAS                    | +4.72                         | 0.282                       |
| G264.322−00.184    | 264.322    | −0.184     | 08:49:32.995          | −44:10:46.19           | IRAS                    | +9.07                         | 0.364                       |
| G285.259−00.049    | 285.259    | −0.049     | 10:31:28.383          | −58:02:07.23           | IRAS                    | +2.14                         | 0.199                       |
| G287.184−00.816    | 287.184    | −0.816     | 10:45:53.955          | −59:57:01.87           | IRAS                    | −14.96                        | 0.195                       |
| G300.958+00.902    | 300.958    | +0.902     | 12:34:39.728          | −61:54:19.57           | MIPSgal                 | −41.67                        | 0.209                       |
| G300.960−00.702    | 300.960    | −0.702     | 12:33:44.636          | −63:30:21.53           | GLIMPSE-Bright          | ...                           | 0.208                       |
| G300.968+01.145    | 300.968    | +1.145     | 12:34:52.771          | −61:39:48.93           | ATLASgal                | −42.96                        | 0.197                       |
| G301.991−00.704    | 301.991    | −0.704     | 12:42:59.051          | −63:33:37.09           | GLIMPSE-Bright          | ...                           | 0.177                       |
| G302.018−00.113    | 302.018    | −0.113     | 12:43:23.547          | −62:58:13.69           | MIPSgal                 | −35.17                        | 0.181                       |
| G302.021+00.251    | 302.021    | +0.251     | 12:43:31.042          | −62:36:24.26           | ATLASgal                | −46.45                        | 0.190                       |

Notes. Central source velocities are determined by hand examination of the four main lines for each source. Where two velocity components are seen, the stronger is listed first. \( T_{\text{rms}} \) gives the noise per channel in the spectrum as measured at the central position in the map.

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)

but did consider them as separate sources (giving us a total of 187 sources) when considering the distributions of measured moments (because they are likely two separate dense molecular clumps at distinct distances as well as velocities).

The positions of maximum integrated intensity within each map were found by making a signal-to-noise ratio (S/N) map from \( M_0 \) and \( \sigma_{M_0} \), setting the poorly sampled three edge pixels to zero, boxcar smoothing by a factor of three (i.e., taking the
of intensity ratios. The parameters of the four main lines (N$_2$H$^+$, as several of our sources exhibit strong spatial variation in line integrated intensity position for each line, but this is desirable value. This process produces a potentially different maximum velocity range used for measuring moments (dashed line).

Results are listed for lines with 5 detections in the narrow ($\sigma$) range used for measuring moments (dashed line).

Table 4

| Name                        | Maximum Integrated Intensity (K km s$^{-1}$) | Offset from Map Center$^a$ (9′′ pixels) | FWHM (km s$^{-1}$) |
|-----------------------------|---------------------------------------------|----------------------------------------|-------------------|
|                            | $N_2$H$^+$ | HNC | HCO$^+$ | HCN | $N_2$H$^+$ | HNC | HCO$^+$ | HCN |                           |
| G263.620–00.530             | 2.47 ± 0.42 | 2.95 ± 0.38 | 5.09 ± 0.39 | 5.18 ± 0.38 | (9, -2) | (4, -5) | (-5, -5) | (-4, -4) | 6.33 ± 1.59 | 5.59 ± 1.09 |
| G264.322–00.184             | 3.58 ± 0.57 | 3.15 ± 0.49 | 3.82 ± 0.56 | 4.16 ± 0.46 | (-9, -2) | (-7, -3) | (-9, -4) | (-4, -3) | 6.18 ± 1.90 | 3.95 ± 4.01 |
| G285.259–00.049             | 4.03 ± 0.25 | 4.34 ± 0.26 | 13.07 ± 0.27 | 12.42 ± 0.28 | (0, -8) | (-1, -8) | (-3, -1) | (-3, -1) | 0.39 ± 13.50 | 5.00 ± 0.37 |
| G287.814–00.816             | 1.65 ± 0.25 | 2.96 ± 0.25 | 7.71 ± 0.26 | 9.12 ± 0.27 | (1, 4) | (-1.2) | (-1.2) | (1, 2) | 3.53 ± 1.99 | 0.42 ± 7.32 |
| G300.958+00.902             | 3.14 ± 0.26 | 3.20 ± 0.28 | 4.39 ± 0.27 | 3.22 ± 0.28 | (3, -5) | (7, 3) | (8, 3) | (6, 1) | 5.62 ± 1.21 | 6.00 ± 0.79 |
| G300.960–00.702             | <1.38       | >1.38   | <1.38   | <1.38   | ...     | ...     | ...     | ...     | 2.20 ± 1.80 | 4.76 ± 0.35 |
| G300.968+01.145             | 6.11 ± 0.24 | 5.83 ± 0.26 | 12.62 ± 0.26 | 16.05 ± 0.27 | (1, -1) | (0, 0) | (0, 0) | (-1, 0) | 5.64 ± 1.40 | 6.00 ± 1.59 |
| G301.991–00.704             | <1.17       | <1.17   | <1.17   | <1.17   | ...     | ...     | ...     | ...     | 10.14 ± 1.40 | 6.53 ± 1.59 |
| G302.018–00.113             | <1.20       | 0.97 ± 0.23 | 1.78 ± 0.24 | <1.20 | ... | (-5, -6) | (-3, 9) | ...     | 7.54 ± 0.75 | 7.36 ± 0.60 |
| G302.021+00.251             | 2.31 ± 0.24 | 3.16 ± 0.25 | 4.37 ± 0.26 | 5.22 ± 0.27 | (-2, 0) | (-2, 0) | (-2, 0) | (-2, 0) | 6.32 ± 1.59 | 5.93 ± 1.09 |

Notes. Results are listed for lines with 5σ detections in the narrow (±2.25 km s$^{-1}$) moment maps, but these measurements report the moments calculated in a range of (±8.25 km s$^{-1}$). Not all integrated intensity measurements at 5σ result in this broader velocity range.

$^a$ Offsets are (x,y) offsets in units of pixels, where each pixel is 9′′. Offsets are relative to the targeted center of the map, which is determined differently for the different input surveys.

$^b$ $N_2$H$^+$ is outside the spectral coverage for sources with $V_{LSR} < -100$ km s$^{-1}$.

This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.

sliding average of three pixels), and identifying the maximum value. This process produces a potentially different maximum integrated intensity position for each line, but this is desirable as several of our sources exhibit strong spatial variation in line intensity ratios. The parameters of the four main lines ($N_2$H$^+$, HNC, HCO$^+$, HCN) at their respective positions of maximum integrated intensity are listed in Table 4.

5. RESULTS

5.1. Detection Statistics and Line Properties

The large size of our data set requires that we set a high level of significance when searching for features to avoid many false positives. With 187 sources, each with 16 lines and 31×31 pixels in each map, we are searching for line detections in nearly 3 million spectra. A 5σ detection threshold should produce one false positive per 1.7 million measurements (for a perfectly normal distribution). We consider this to be an acceptably small level of contamination and refer to a 5σ detection as a robust detection. Additional selection criteria combined with a lower detection threshold could be used to search for additional weak lines. For instance, to improve the completeness of $^{13}$CO$^+$ detections we could adopt a lower 3σ threshold while constraining the search to locations with significant HCO$^+$ flux.
Our robust detection rates of the four main lines (N$_2$H$^+$, HNC, HCO$^+$, and HCN) were high (>90%) for the HOPS, ATLASGAL, and IRAS catalogs, and lower (<60%) for sources chosen based on the morphology of Spitzer emission (see Figure 4). Detection rates were comparable for the HOPS, ATLASGAL, and IRAS samples, and similar for all four species. Five additional species had robust detections: C$_2$H, $^{13}$CS, SiO, H$_{13}$CO$^+$, and H$_{13}$CN. These detection rates are presented in Figure 5. C$_2$H, in particular, was commonly seen, with detection rates between 10% and 90% for the six different surveys. Again, the HOPS, ATLASGAL, and IRAS catalogs produced more robust detections than the catalogs based on the morphology of Spitzer emission. The low-detection rates of the three input catalogs based on Spitzer morphology are likely due to these catalogs identifying features which are not truly associated with dense clumps. For instance, 10% to 20% of the IRDC candidates in the Peretto & Fuller (2009) catalog are not detected in the Herschel Hi-GAL survey (Peretto et al. 2010) and only 58% of the IRDC candidates in the Simon et al. (2006) catalog are detected in CS (Jackson et al. 2008). These non-detections suggest that the IRDC catalogs contain sources with a range of column densities, including sources with low column densities that do not have sufficient column density to be observed with the sensitivity limits of this survey. Table 5 presents the detections and non-detections of lines for all the sources.

The detection statistics correspond to the brightest integrated emission anywhere in the map, not necessarily at the center of the map. Each input catalog provides a central position of the source, which was used as the center of the map. The positions of maximum integrated intensity tend to be clustered at the center of our images (see Figure 6) with 50% of maximum integrated intensity detections for each of the four main lines occurring within $40''$ of the map center. This suggests that the input catalog positions are good choices for the center of the map.

The observed distributions of the integrated intensities and line widths of the four main species (N$_2$H$^+$, HNC, HCO$^+$, and HCN) at the brightest point in each map are displayed in Figures 7 and 8. Again, the detection threshold is $M_0 > 5\sigma$ in the narrow ($\pm 2.25$ km s$^{-1}$) integration range, but the integrated
intensities shown in Figures 7 and 8 and reported in Table 4 are based on the broader range (±8.25 km s$^{-1}$); some lines are no longer 5σ measurements when using the broader velocity integration range.

The integrated intensities for the four main species at their brightest location in each map show broadly similar distributions. All are incomplete below 2 K km s$^{-1}$ due to our noise and detection level. Two sources have extremely bright and broad HCO$^+$ lines, with $M_0 > 20$ K km s$^{-1}$, possibly indicating the presence of outflows. HNC has relatively fewer lines which are both broad and bright. Although integrated intensity is a distance-dependent measurement, most sources are detected in all four lines at the same velocity (and thus distance) or in none of these lines. Therefore, the similarity of integrated intensity distributions shows that the line luminosity distributions for these transitions are similar for the majority of these sources (see Section 5.3.1 for some counter-examples).

We calculate an effective $\Delta V_{\text{FWHM}}$ from the second moment ($M_2$) with the formula for a Gaussian profile ($\Delta V_{\text{FWHM}} = \sqrt{8 \ln 2 \times M_2}$), despite the fact that many lines deviate from a Gaussian profile. $\Delta V_{\text{FWHM}}$ are often reported as a proxy for second moment, so we report this effective $\Delta V_{\text{FWHM}}$ to facilitate comparison with other studies. We report this quantity only for HNC and HCO$. N_2H^+$ and HCN are excluded because their hyperfine structure prohibits making a line-width measurement solely from our moment maps.

We compare the HCO$^+$ and HNC line-width distributions in Figure 8 for sources where $M_2/\sigma_{M_2} > 3$. We break down the HCO$^+$ distribution based on whether $H^{13}$CO$^+$ is detected for a given source. The detection of this rare isotope typically indicates an optically thick HCO$^+$ line (although a non-detection of $H^{13}$CO$^+$ is not a guarantee that HCO$^+$ is optically thin). The distributions of $\Delta V_{\text{FWHM}}$ for HCO$^+$ and HNC are broadly similar. We apply a two-sided Kolmogorov–Smirnov (K-S) test

Table 5

| Name                  | N$_2$H$^+$ | $^{13}$CS | HNC | HCO$^+$ | HCN | C$_2$H | SiO | H$^{13}$CO$^+$ | H$^{13}$CN |
|-----------------------|------------|----------|-----|---------|-----|--------|-----|----------------|------------|
| G263.620−00.530       | 1          | 0        | 1   | 1       | 1   | 1      | 0   | 0              | 0          |
| G264.322−00.184       | 1          | 0        | 1   | 1       | 1   | 0      | 0   | 0              | 0          |
| G285.259−00.049       | 1          | 0        | 1   | 1       | 1   | 1      | 0   | 0              | 0          |
| G287.814−00.816       | 1          | 0        | 1   | 1       | 1   | 1      | 0   | 0              | 0          |
| G300.958+00.902       | 1          | 0        | 1   | 1       | 1   | 0      | 0   | 0              | 0          |
| G300.960−00.702       | 0          | 0        | 0   | 0       | 0   | 0      | 0   | 0              | 0          |
| G300.960+01.145       | 1          | 0        | 1   | 1       | 1   | 1      | 0   | 0              | 1          |
| G301.991−00.704       | 0          | 0        | 0   | 0       | 0   | 0      | 0   | 0              | 0          |
| G302.018−00.113       | 0          | 0        | 1   | 1       | 0   | 0      | 0   | 0              | 0          |
| G302.021+00.251       | 1          | 0        | 1   | 1       | 1   | 1      | 0   | 0              | 0          |

Notes. Robust detections correspond to 5σ integrated intensity detections excluding the 3 pixels (27") on the edge of each map. Detection statistics are not shown for H41α, CH$_3$CN, HC$_3$N, $^{13}$C$_3$S, HC$_{13}$CCN, HNCO 41, or HNCO 40, which have no robust detections. One corresponds to a robust detection and zero indicates no robust detection.

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)

Figure 6. Radial offset of maximum integrated intensity for each of the four main MALT90 pilot lines (N$_2$H$^+$, HNC, HCO$^+$, and HCN) from the center of the map. Offsets are relative to the targeted center of the map, which is determined differently for the different input surveys. Pointing error is estimated to be less than 10".
and find that we cannot reject the hypothesis that the HNC and HCO$^+$ line widths are drawn from the same population when considering just the HCO$^+$ line widths in sources without an $^{13}$CO$^+$ detection ($p$-value = 9%) or all the HCO$^+$ line widths ($p$-value = 32%).

The line-width distributions shown in Figure 8 are the line widths at the positions of maximum integrated intensity for each molecular line transition. If we restrict our analysis to sources for which the positions of maximum integrated intensity for HCO$^+$ and HNC are within one 9$''$ pixel (within 13$''$ to include diagonally adjacent pixels) we can compare line widths at roughly the same position. Figure 9 shows the results of this comparison for sources where $M_2/\sigma_{M_1} > 3$ in both lines. For the sources with an $^{13}$CO$^+$ detection (i.e., where HCO$^+$ is likely to be optically thick) the HCO$^+$ line width is typically larger than the HNC line width ($\langle \Delta V_{\text{FWHM}}(\text{HCO}^+) - \Delta V_{\text{FWHM}}(\text{HNC}) \rangle = 1.15$). For the sources without an $^{13}$CO$^+$ detection, the line-width ratios are correlated and centered around unity ($\langle \Delta V_{\text{FWHM}}(\text{HCO}^+) - \Delta V_{\text{FWHM}}(\text{HNC}) \rangle = 0.98$). This suggests that the sources with $^{13}$CO$^+$ detections do have optically thick HCO$^+$ emission, and that this is what produces their larger line widths. In the pilot survey, we have no rare isotopologue of HNC to study where HNC might be optically thick, but the main MALT90 survey will include...
Figure 9. Comparison of the effective $\Delta V_{\text{FWHM}}$ of the two strong single-component lines (left: HNC and right: HCO$^+$) where the positions of maximum integrated intensity are within 13$''$ and $M_2/\sigma_{M2} > 3$. The dashed line is unity. Crosses indicate sources with H$^{13}$CO$^+$ detections where the HCO$^+$ line width tends to have larger than the HNC line width. For the sources without H$^{13}$CO$^+$ detections, the line widths are on average the same for both HCO$^+$ and HNC.

HN$^{13}$C instead of H$^{13}$CN (HCN, because of its hyperfine structure, is less likely to be optically thick for similar line intensities).

5.2. Choice of Input Catalog

The first goal of the MALT90 pilot survey was to select an input catalog for the full MALT90 survey. Of the six catalogs tested, only HOPS, ATLASGAL, and IRAS had sufficiently high (>90%) detection rates to be used as input catalogs for the main MALT90 survey. There are significant scientific and logistical benefits to using a single catalog when selecting sources. The main advantages are the ability to use a simple and uniform criteria for choosing sources, the ability to compare our observed line properties against properties of the input catalog, and the ability to describe the significance of non-detections. The ATLASGAL catalog provides the optimal source list for MALT90. There are three major factors in favor of using ATLASGAL: (1) catalog size, (2) a broad range of source positions and velocities, and (3) a range of evolutionary states.

ATLASGAL provides a much larger catalog than HOPS or the Beltrán et al. (2006) survey of IRAS sources. Schuller et al. (2009) report from the initial results of the survey about 6000 sources brighter than 0.25 Jy in 95 deg$^2$ in the Galactic range $-30^\circ < l < +15^\circ$ and $+21^\circ < l < +30^\circ$ with $|b| < 1^\circ$. In contrast, the Beltrán et al. (2006) survey contains 235 sources and HOPS (Walsh et al. 2008) is expected to contain a few hundred bright NH$_3$ sources. Neither HOPS nor IRAS contains a sufficient number of sources for the science goals of MALT90.

ATLASGAL sources appear to sample many Galactic structures. Figure 10 shows the Galactic longitude and velocity of sources with detections (using hand-determined velocities) plotted on the Dame et al. (2001) CO map. The Dame et al. (2001) CO map is presented as a longitude–velocity diagram integrated over $-2^\circ < b < 2^\circ$ and has units of K arcdeg. The positions of our sources in this plot all fall within the 0.3 K arcdeg CO contour and most cluster in the portions of stronger CO emission, as expected for dense, star-forming gas. The presence of ATLASGAL sources at many positions in the longitude–velocity diagram indicates that this catalog is detecting sources in a range of Galactic locations.

ATLASGAL sources cover a range of evolutionary states. The initial results of ATLASGAL found that two-thirds of the sources do not have a mid- or far-infrared counterpart in the Midcourse Space Experiment (MSX) and IRAS catalogs. A closer inspection of IRAS/MSX dark sources in more sensitive Spitzer GLIMPSE/MIPSGAL images reveals that many of them associated with weaker infrared sources but still a considerable fraction of the submillimeter emission appear dark in the Spitzer images (e.g., Figures 13 and 14 of Schuller et al. 2009) and work on the first compact source release catalog demonstrates that ATLASGAL will provide enough sources in each evolutionary state as assessed by the Spitzer emission morphology scheme shown in Figure 1.

Figure 10. Distribution of MALT90 pilot sources in velocity and Galactic longitude, overlaid on the Galactic CO distribution from Dame et al. (2001) integrated over Galactic latitude. The CO contours are at 0.3, 1, 3, and 10 K arcdeg. Different input catalogs are labeled as follows: yellow, Dark GLIMPSE source; purple, Bright GLIMPSE source; green, MIPSGAL source; red, HOPS source; blue, IRAS source; orange, ATLASGAL source. Sources with no detected line emission (and thus no velocity) are omitted. In addition, four IRAS sources with Galactic longitude between $-70$ and $-100$ deg were omitted to display the remaining sources at a larger scale. These four omitted sources all also lie within the CO 0.3 K arcdeg emission contour.
We thus choose ATLASGAL as the sole input catalog for the MALT90 survey because it meets all our requirements for a source list. ATLASGAL sources had high detection rates in this pilot survey, include a diversity of evolutionary states, and cover a broad range of Galactic positions. Choosing ATLASGAL as the sole input catalog also provides the benefits of having a single uniform catalog when selecting sources. We can choose our sources with a uniform set of criteria and compare our MALT90 measurements against ATLASGAL catalog properties such as the flux and extent of 870 μm emission.

5.3. MALT90 Survey Strategy

The second goal of the MALT90 pilot survey was to test the observing set up and verify that it allows us to achieve our science goals. MALT90 is fundamentally a mapping survey; although some science goals (such as determining distances to clumps) could be achieved with a single pointing, the majority of our science goals rely on maps. Our configuration allows us to map sources in multiple lines at high spectral resolution. Maps of multiple lines allow us to study the chemical variation within a clump, which is most useful if clumps are typically spatially resolved and at least sometimes exhibit strong chemical variation. Mapping at high velocity resolution (0.11 km s\(^{-1}\)) allows us to study spatial variation in line profiles the may indicate changes in the strength of turbulence, large scale motions (rotation, shear, infall, or outflow), or multiple velocity components. The pilot survey allowed us to verify that our OTF maps had sufficient sensitivity and that we could make maps without significant artifacts.

5.3.1. Mapping Multiple Dense-gas Tracers to Reveal Chemistry

We see strong chemical variation in the MALT90 pilot sources which validates our decision to map multiple lines in these sources. All four of our main lines (N\(_2\)H\(^+\), HCN, HCO\(^+\), and HNC) are ground-state transitions of molecules with similar critical densities. As tracers of dense gas, the emission from these lines typically show similar morphologies in MALT90 pilot sources, but this is not always the case. Figure 11 shows two example sources where N\(_2\)H\(^+\) varies significantly with respect to the other species. Figure 11 shows one source where the maximum N\(_2\)H\(^+\) integrated intensity is a factor of 4–8 times weaker than the other three main lines. Conversely, the other source in Figure 11 has N\(_2\)H\(^+\) emission that is twice as strong as that of HCN, HCO\(^+\), or HNC. Large variation in the HCO\(^+\)/N\(_2\)H\(^+\) integrated intensity ratio in high-mass star-forming regions has been noted before (e.g., Turner & Thaddeus 1977; Walsh & Burton 2006). Thus, the combination of mapping in several lines simultaneously gives us the most complete picture of the spatial distribution of the various molecules, which is crucial to studying variations in the chemistry with the MALT90 sources.

5.3.2. Mapping Strategy

Mapping artifacts are seen in many of our maps, typically manifesting as stripes in the direction of scans. Our sources were generally mapped with scans of constant Galactic longitude so that each strip in Galactic longitude uses the same reference spectrum. Noise or gain variations in this reference spectrum can therefore produce stripes in the map, and this phenomenon is particularly prevalent in sources observed in bad weather. We chose to map using scans of constant Galactic longitude for the pilot survey because most extended structures in the Galactic plane are parallel to the plane. Thus, noise stripes are easier to identify, since they typically run perpendicular to real features. We mapped two sources (G305.887 + 00.016 and G308.058 − 00.397) in both Galactic longitude and latitude to see if this would mitigate the striping. Figure 12 shows the two individual maps for G308.058 − 00.397 as well as the combination of both maps for a signal-free \(^{13}\)C\(^{34}\)S cube. The striping visible in the scan direction in both individual maps is significantly reduced in the combined image. We therefore decided to map using scans of both constant Galactic longitude and latitude in the full MALT90 survey.

5.3.3. The Value of High-resolution Velocity Information

Figure 13 shows the central portion of the maps for the source G321.935 − 00.007 in HNC and HCO\(^+\). The HCO\(^+\) line shows self-absorption at the systemic velocity (traced by the HNC
Figure 12. Zeroth moment (integrated intensity) maps of $^{13}$C$^{34}$S in G308.058$-00.397$. $^{13}$C$^{34}$S has very low abundance, so these maps show only noise. In panel (a) the map was made with scans of constant Galactic longitude, which is the default mode for the MALT90 pilot survey. In panel (b) the map was made with scans of constant Galactic latitude. In panel (c), the two individual maps were combined, reducing the striping artifacts visible in maps (a) and (b). This reduction of artificial structure motivates combining maps scanned in both directions in the full MALT90 Survey.

Figure 13. HCO$^+$ (thick/black) and HNC (thin/red) line profiles over the central portion of the G321.935$-00.007$ cube. The HNC spectra has been scaled by a factor of 0.5. The HCO$^+$ line shows a strong dip at the systemic velocity, but the relative strengths of the blue and red wings vary throughout this map. Adjacent spectra are separated by 9$''$.

which shows little or no non-Gaussianity). In the lower-right portion of the map, this self-absorption shows an asymmetric profile with brighter blueshifted emission. Such a profile is characteristic of infall of cold gas toward a hot central source (e.g., Mardones et al. 1997). This characteristic shape is not present in the upper left of the map, where we see a redshifted profile usually associated with expansion. It is possible that infall is happening only in part of this source or that other kinematic complexity is present; the large variance of this complex line shape over the source demonstrates the value of mapping at high velocity resolution.

5.3.4. Studying Different Stages of Evolution

The many lines observed in MALT90 provide information about the evolutionary state of the clumps observed. This information can be combined with Spitzer morphological
classification and dust temperature determination from spectral-energy distribution fitting (e.g., Rathborne et al. 2010; Peretto et al. 2010) to constrain the evolutionary state of a clump. As a short example we present three sources in different Spitzer morphological states and show what information can be gained from the molecular lines in each case.

Figure 14 shows G330.873−00.361, a clump drawn from the HOPS survey catalog and classified as an H ii region from the Spitzer GLIMPSE/MIPSGAL images due to its strong extended 8 and 24 μm emission. The presence of CH$_3$CN ($J_K = 5_1 − 4_1$) emission identifies the hot core associated with a massive protostar. This location is also the position of maximum integrated intensity for most of the other molecules (HCN, HNC, SiO, $^{13}$CS), but N$_2$H$^+$ peaks in the south as the position of another 24 μm point source.

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Figure 15 shows G335.075−00.411, a clump drawn from the HOPS survey catalog and classified as protostellar from the Spitzer GLIMPSE/MIPSGAL images due to the presence of 24 μm point sources within a dark extinction feature without extended 8 or 24 μm emission. The spatial coincidence of the 24 μm point sources and the 8 μm extinction feature suggests that the 24 μm point sources are associated with the clump, and the MALT90 pilot survey data confirms this association. The N$_2$H$^+$ integrated intensity contours trace the 8 μm emission extinction feature. There is SiO emission at the same velocity as the position of the brightest 24 μm point source. Since SiO emission is normally associated with outflow activity in protostars (e.g., López-Sepulcre et al. 2011), a detection of this line at the same velocity as the clump is strong evidence that the 24 μm point source is associated with this clump.

Figure 16 shows G322.668−00.038, a clump drawn from the GLIMPSE-Dark catalog and classified as quiescent from the Spitzer GLIMPSE/MIPSGAL images due to the lack of 8 or 24 μm emission inside the 8 μm extinction feature. As a quiescent clump in the early stages of evolution, this object displays less complex chemistry than clumps in more evolved stages with only the four main lines (N$_2$H$^+$, HNC, HCO$^+$, and HCN) detected. The HNC integrated intensity emission shows two distinct peaks associated with two of the darkest 8 μm extinction features. The velocity field of HNC shows that these two peaks are at very similar velocities (−64 km s$^{-1}$ and −65.6 km s$^{-1}$), strongly suggesting that both peaks are at the same distance and that the entire extinction feature is a single physical object. We use the Clemens (1985) rotation curve to calculate a kinematic distance for this clump; the near distance is 4.27 kpc and the far distance is 9.25 kpc. Because we see the clump as an extinction feature against the diffuse Galactic background, it is reasonable to assume that the near distance is
detection rates than choosing sources identified based on studying many aspects of high-mass star formation. By an order of magnitude, and providing a valuable database for 3000 candidate dense molecular clumps, increasing this sample clumps. The full survey is underway and plans to map a total of the largest sets of 90 GHz molecular line maps for dense molecular reduced data cubes and uniform moment maps which facilitate able through this paper and the MALT90 Web site, including distribution of dense molecular clumps associated with high-mass star formation, and the galactic dis-
sible with this survey including studying chemical variation, MALT90 pilot survey and highlighted some of the science pos-
rect. The MALT90 map therefore allows us (1) to identify which extinction features are likely a single physical object versus a chance projection and (2) to assign a distance which is useful for any further study of this object.

6. CONCLUSION

We have described the MALT90 pilot survey, carried out to demonstrate the feasibility of the MALT90 survey, identify the best input catalog for choosing MALT90 targets, and optimize the survey parameters. We choose the ATLASGAL (Schuller et al. 2009) catalog as our source list on the basis of its high detection rates for the main four survey lines (>90% for N2H+, HNC, HCO+, and HCN) and the large number of dense molecular clumps in different evolutionary stages in this catalog. The surveys which provided a prior selection for regions of high column density, either from optically thin dust (ATLASGAL at 870 μm, the Beltrán et al. (2006) survey at 1.2 mm) or another dense gas tracer (NH3 from HOPS), produced much higher detection rates than choosing sources identified based on Spitzer emission morphology without this prior.

We have briefly summarized the data obtained from the MALT90 pilot survey and highlighted some of the science possible with this survey including studying chemical variation, the kinematics of massive dense clumps, and the galactic distribution of dense molecular clumps associated with high-mass star formation. We have made the full data set publicly avail-
able through this paper and the MALT90 Web site, including reduced data cubes and uniform moment maps which facilitate easy inspection of the data. This collection is already one of the largest sets of 90 GHz molecular line maps for dense molecular clumps. The full survey is underway and plans to map a total of 3000 candidate dense molecular clumps, increasing this sample by an order of magnitude, and providing a valuable database for studying many aspects of high-mass star formation.

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REFERENCES

Bergin, E. A., & Tafalla, M. 2007, ARA&A, 45, 339
Brown, P. D., Charnley, S. B., & Millar, T. J. 1988, MNRAS, 231, 409
Carey, S. J., Noriega-Crespo, A., Mizuno, D. R., et al. 2009, PASP, 121, 76
Clemens, D. P. 1985, ApJ, 295, 422
Dame, T. M., Hartmann, D., & Thaddeus, P. 2001, ApJ, 547, 792
Fazio, G. G., Hora, J. L., Allen, L. E., et al. 2004, ApJS, 154, 10
Fuller, G. A., Williams, S. J., & Sridharan, T. K. 2005, A&A, 442, 949
Gerin, M., Kaźmierczak, M., Jastrzebska, M., et al. 2011, A&A, 525, A116
Gibson, D., Plume, R., Bergin, E., Ragan, S., & Evans, N. 2009, ApJ, 705, 123
Hirotta, T., Yamamoto, S., Mikami, H., & Ohishi, M. 1998, ApJ, 503, 717
Jackson, J. M., Finn, S. C., Rathborne, J. M., Chambers, E. T., & Simon, R. 2008, ApJ, 680, 349
Ladd, N., Purcell, C., Wong, T., & Robertson, S. 2005, PASA, 22, 62
Lo, N., Cunningham, M. R., Jones, P. A., et al. 2009, MNRAS, 395, 1021
López-Sepulcre, A., Walmsley, C. M., Cesaroni, R., et al. 2011, A&A, 526, L2
Mardones, D., Myers, P. C., Tafalla, M., et al. 1997, ApJ, 489, 719
Peretto, N., & Fuller, G. A. 2009, A&A, 505, 405
Purcell, C. R., Balasubramanyam, R., Burton, M. G., et al. 2006, MNRAS, 367, 553
Rathborne, J. M., Jackson, J. M., Chambers, E. T., et al. 2010, ApJ, 715, 310
Rawlings, J. M. C., Redman, M. P., Keto, E., & Williams, D. A. 2004, MNRAS, 351, 1054
Rieke, G. H., Young, E. T., Engelbracht, C. W., et al. 2004, ApJS, 154, 25
Schilke, P., Walmsley, C. M., Pineau des Forêts, G., & Flower, D. R. 1997, A&A, 321, 293
Schuller, F., Menten, K. M., Contreras, Y., et al. 2009, A&A, 504, 415
Shirley, Y. L., Evans, N. J., II, Young, K. E., Knez, C., & Jaffe, D. T. 2003, ApJS, 149, 375
Shukla, H., Yun, M. S., & Scoville, N. Z. 2004, ApJ, 616, 231
Simon, R., Jackson, J. M., Rathborne, J. M., & Chambers, E. T. 2006, ApJ, 639, 227
Turner, B. E., & Thaddeus, P. 1977, ApJ, 211, 755
Walsh, A. J., & Burton, M. G. 2006, MNRAS, 365, 321
Walsh, A. J., Lo, N., Burton, M. G., et al. 2008, PASA, 25, 105
Watson, C., Povich, M. S., Churchwell, E. B., et al. 2008, ApJ, 681, 1341
Williams, J. P., Blitz, L., & McKee, C. F. 2000, in Protostars and Planets IV, ed. V. Mannings, A. P. Boss, & S. S. Russell (Tucson, AZ: Univ. Arizona Press), 97
Wu, J., Evans, N. J., Shirley, Y. L., & Knez, C. 2010, ApJS, 188, 313