The MUSTANG Galactic Plane Survey (MGPS90) Pilot

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Abstract

We report the results of a pilot program for a Green Bank Telescope MUSTANG-2 Galactic Plane survey at 3 mm (90 GHz), MGPS90. The survey achieves a typical 1σ depth of 1–2 mJy beam−1 with a 9′ beam. We describe the survey parameters, quality assessment process, cataloging, and comparison with other data sets. We have identified 709 sources over seven observed fields selecting some of the most prominent millimeter-bright regions between 0 deg < l < 50 deg (total area ≈7.5 deg2). The majority of these sources have counterparts at other wavelengths. By applying flux selection criteria to these sources, we successfully recovered several known hypercompact H II (HCH II) regions but did not confirm any new ones. We identify 126 sources that have mm-wavelength counterparts but do not have cm-wavelength counterparts and are therefore candidate HCH II regions; of these, 10 are morphologically compact and are strong candidates for new HCH II regions. Given the limited number of candidates in the extended area in this survey compared to the relatively large numbers seen in protoclusters W51 and W49, it appears that most HCH II regions exist within dense protoclusters. Comparing the counts of HCH II to ultracompact H II (UCH II) regions, we infer the HCH II region lifetime is 16%–46% that of the UCH II region lifetime. We additionally separated the 3 mm emission into dust and free–free emission by comparing with archival 870 μm and 20 cm data. In the selected pilot fields, most (>80%) of the 3 mm emission comes from plasma, either through free–free or synchrotron emission.

Supporting material: machine-readable table

1. Introduction

Surveys of the Galactic plane in the millimeter regime are essential for measuring the gas and dust involved in star formation. Several continuum surveys have covered the complete plane from the far-infrared through 1 mm (Molinari et al. 2010; Aguirre et al. 2011; Ginsburg et al. 2013; Csengeri et al. 2014; Eden et al. 2017; Elia et al. 2017). In the millimeter/submillimeter regime, these surveys have resolution 15″ or worse. In the centimeter regime, large-area Galactic plane surveys have been conducted at 4 cm and longer wavelengths at resolutions generally ∼1″ or coarser (Goveen et al. 2005a; Hoare et al. 2012; Beuther et al. 2016; Medina et al. 2019).

Emission at 3 mm (90 GHz) consists of a combination of dust, free–free, and synchrotron continuum emission. Between 1 mm and 4 cm, there are no existing Galactic plane surveys. This wavelength regime represents the global minimum in typical Galactic spectral energy distributions (SEDs). At 3 mm, most dust emission is optically thin; very few regions have high enough column density, N > 3 × 1026 cm−2 on ∼0.1–1 pc scales, to reach an optical depth of τ3mm > 1. Similarly, almost all H II regions exhibit optically thin free–free emission at 3 mm; only the densest of hypercompact H II (HCH II) regions are optically thick out to such high frequencies. Anomalous Microwave Emission peaks somewhere in the 10–60 GHz regime and remains a substantial fraction of the total emission on large angular scales out to ∼100 GHz, though so far, most observations on smaller (≤10′) scales have been limited to lower (<50 GHz) frequencies (Dickinson et al. 2018).

Thermally emitting dust follows a modified Planck function of a typical temperature of 10–30 K in Galactic clouds; its intensity therefore peaks near 1–3 THz, placing the 90 GHz MGPS90 observations firmly on the Rayleigh–Jeans tail. At
90 GHz, the dust flux density is set by the dust column density \( N_d \), the dust temperature \( T_d \), and the dust opacity \( \kappa_d \):
\[
S_{\nu, d} \propto \kappa_d B_\nu(T_d)N_d,
\]
where \( B_\nu(T_d) \) is the Planck function. The dust opacity as a function of frequency can be modeled as a power law:
\[
\kappa_\nu \propto \nu^\beta,
\]
where \( \beta \) is the dust emissivity index. Ongoing and future massive star formation is associated with dust emission, and we expect to see dust emission at 90 GHz in the MGPS90 fields.

The flux density from optically thin free–free emission is roughly flat as a function of frequency, \( S_{\nu, ff} \propto \nu^0 \), where \( \alpha = -0.12 \) is the spectral index, and we expect almost all free–free emission to be optically thin at the observed frequency (Condon & Ransom 2007, 2016; Wilson et al. 2009).

Synchrotron emission generally has a steep negative spectral index and so it decreases in intensity as a function of an increasing frequency, \( S_{\nu, synch} \propto \nu^{-\alpha} \), with \( \alpha \approx -1 \) to \(-2\). At 90 GHz, we expect to detect synchrotron emission from Galactic supernova remnants, nonthermal filaments (in the Galactic center), and extragalactic sources.

The only objects that tend to peak at 3 mm are the most extremely dense and compact H II regions. To reach an optical depth of \( \tau_{90\text{GHz}} \approx 1 \) at 90 GHz, an H II region must have an emission measure of \( EM \geq 10^{16} \text{cm}^{-6} \text{pc} \). Such high EM is only reached in extremely dense regions (e.g., Galván-Madrid et al. 2009); for example, an \( r \approx 100 \) au H II region would reach \( \tau_{90\text{GHz}} \approx 1 \) at density \( n \approx 10^7 \text{cm}^{-3} \) (Wilson et al. 2009; Condon & Ransom 2016). Such compact and dense H II regions are expected to be a short phase in the early evolution of massive stars, occurring shortly after the stars contract onto the main sequence for a brief period before they expand into less dense, larger H II regions (Wood & Churchwell 1989a). A census of 3 mm peaked, compact sources can provide a measurement of the actively forming massive star population of the Galaxy or, alternatively by comparison to other stages, can be used to constrain the lifetime of this early stage in H II region evolution.

MUSTANG-2 (Dicker et al. 2014) is a 215 element bolometer array operating on the 100 m Robert C. Byrd Green Bank Telescope\(^{17} \) (GBT) with a wide (75–105 GHz) bandwidth and a 4/25 field of view.\(^{18} \) The Transition Edge Sensor detectors are read out using a microwave multiplexing readout (unix). Typical observing modes consist of different on-the-fly mapping scans—either small daisy scans for arcminute sized targets or larger raster scans in perpendicular directions used in the data presented in this paper. Both scan patterns are designed to maximize cross linking on many timescales so as to enable the removal of 1/f noise from the instrument and the atmosphere. In the large bandwidth of MUSTANG-2, line contamination is generally negligible.

We present the first component of an ongoing 3 mm survey with the MUSTANG-2 instrument on the GBT with a 9\(^{\circ}\) resolution. When complete, this survey will cover most of the northern Galactic plane within \(|b| < 0.5\). This pilot project selected some of the most actively star-forming regions in the Galaxy to maximize the discovery probability of HCHII regions. The full survey will be a blind survey of the Galactic plane.

### 2. Observations

A summary of the reported observations is given in Tables 1 and 2.

The images from this project are released at [doi:10.7910/DVN/HPATJB].

#### 2.1. Calibration

A consistent calibration procedure was carried out for each observation. Known point sources were observed at regular intervals each night.

1. A calibration for the detector array, i.e., relative calibration between the individual detectors, is found using a skydip and the opacity at 90 GHz as given by Control Library for Operators and Engineers\(^{19} \) (CLEO) to get each timestream into the antenna temperature.
2. A map is made in IDL (in azimuth/elevation coordinates) of each scan on a calibrator, which is chosen to be an unresolved (pointlike) source. Romero et al. (2020) describe in detail the IDL pipeline for MUSTANG-2 (MUSTANG IDL Data Analysis System, MIDAS)
   (a) A single 2D Gaussian is fit to the point source to measure its centroid location.
   (b) Fixing the centroid as found above, a double Gaussian is fit. The two Gaussian components share a common center; the central Gaussian represents the telescope main beam, and the second Gaussian represents the first sidelobe of the beam response.

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\(^{18}\) [http://www.gb.nrao.edu/mustang/](http://www.gb.nrao.edu/mustang/)

\(^{19}\) [http://www.gb.nrao.edu/~rmaddale/CLEOManual/](http://www.gb.nrao.edu/~rmaddale/CLEOManual/)
Table 2
Observing Session Dates and Lengths

| Session Number | Session Start | Session Length (hr) | Beam Peak Major (arcsec) | Minor (arcsec) | Beam Area (arcsec²) | θpeak |
|----------------|---------------|---------------------|--------------------------|---------------|---------------------|-------|
| 01             | 2018 Mar 24 08:00 UT | 3.50               | 9.7 ± 0.4                | 9.1 ± 0.2     | 117 ± 9             | 0.85  |
| 02             | 2018 Mar 31 07:30 UT | 4.50               | 10.0 ± 0.3               | 9.2 ± 0.5     | 126 ± 17            | 0.83  |
| 03             | 2018 May 1 06:15 UT  | 4.25               | 10.0 ± 0.5               | 9.0 ± 0.2     | 126 ± 4             | 0.81  |
| 04             | 2018 Jun 15 05:30 UT | 3.25               | 11.1 ± 0.7               | 8.8 ± 0.3     | 127 ± 6             | 0.87  |
| 05             | 2019 Jan 31 11:45 UT | 2.75               | 10.0 ± 0.4               | 9.3 ± 0.3     | 133 ± 11            | 0.79  |

Note. The tabulated times are those in the maps (just in the scans that were used to make a given map). The beam peak major and minor columns show the average and standard deviation fit parameters in FWHM units of the main peak toward each of the calibrators. The beam area is the integrated area under the two-dimensional beam and includes sidelobe contributions. The θpeak column measures how much of the beam area is in the central Gaussian beam; it is the ratio of the area of the Gaussian to the measured beam area. The data are peak-calibrated, so this number indicates the fraction (~20%) of the peak flux that is spread into the surrounding larger area (~20°). In G34, only six of the constant-latitude scans were completed, so only the bottom 1/3 of map has full cross linking.

(c) The beam solid angle is calculated both from the fitted model parameters and from the sum of pixel values within a 60'' aperture. These measurements were consistent, so we used the analytically derived solid angles from the fitted model parameters. These measurements are reported in Table 2.

3. The peaks of secondary calibrators are normalized by the mean flux density for each specific secondary calibrator. These peaks are tied to a primary calibrator that is scaled to the expected peak in Jy beam⁻¹. The expected peak is determined from planetary models if a planet is available, or by interpolation using available Atacama Large Millimeter/submillimeter Array (ALMA) data (Fomalont et al. 2014; van Kempen et al. 2014) if no planet with a suitable flux model is accessible. The scaling is linearly interpolated between calibration scans.

(b) Conversion to a Rayleigh–Jeans brightness temperature (in K; see e.g., Condon & Ransom 2016) accounts for the beam solid angle. As such, the beam solid angles are interpolated between scans.

4. Calibration to Jy, conversion from Jy beam⁻¹ to Kelvin, opacities, and pointing offsets are recorded in an IDL save file and are applied to the processing of the time ordered data taken on the science target (in this case, scans of the Galactic plane).

The absolute accuracy of these calibrations is about 10%. Some of this uncertainty is from the extrapolation in time and frequency of the ALMA sources (the ALMA band is different from MUSTANG-2 but there are measurements at ~100 and 91 GHz), some is the error in the point-source fluxes from ALMA, and some is from our knowledge of the optical depth τ90 GHz during the observations (for which we use archival weather data and models of the atmosphere).

2.2. Map Making

Maps of the science fields were made using MUSTANG-2’s MINKASI²¹ (J. Sievers et al. 2020, in preparation) data reduction pipeline, which is based on the maximum likelihood pipeline written for the Atacama Cosmology Telescope (ACT; Dünner et al. 2013). We used smoothed power spectra from a singular value decomposition (SVD) of the data on a scan by scan basis to obtain a noise model. This model does not work well if there are strong sources. By subdividing timestreams and taking power spectra of each segment, it is possible to identify power spectra taken from parts of the timestreams with strong sources as there is a significant increase in the signal band (~0.1–15 Hz). These regions are flagged and an average power spectrum is calculated from the median of the remaining segments.

We followed an iterative process to obtain the best maps. A map is made, the result then clipped at some level above any artifacts in that iteration, and the results are subtracted from the timestreams. In each loop, the clipping level was reduced and the noise model recalculated. In the last loops (in which all strong signal should have been removed), the full SVD noise model could be used (which tended to give better results on faint features). For W33, three iterations produced optimal results; the other regions required more iterations.

For some fields, notably G34, we only obtained scans in one direction. Future observations filling in the orthogonal scan direction will be needed to eliminate the resulting scan direction striping features.

The map making process assumes the mean incoming intensity is zero. This assumption encodes a large angular scale filter such that angular scales larger than ~4/25 are not present in the data. This filtering is visible as negative bowls in the images, especially in the Sgr B2/Galactic Center field. The processed images are shown in Figures 1–7.

2.3. Sensitivity and Beam Size

The effective beam size in the delivered maps is the convolution of the intrinsic FWHM = 8″1 beam with a FWHM = 4″ Gaussian kernel, resulting in a 9″ beam. This smoothing suppresses sub-beam-scale noise at a modest cost in beam area. The errors per beam reported in Table 1 correspond to these smoothed images.

2.4. Pointing Accuracy

Several corrections to the raw timestream data were required to produce maps. Individual scans were noted to have point sources shifted by up to half a beam (~4″), indicating a timing error between the MUSTANG-2 pointing data and the true telescope pointing. To ensure that point sources were coincident in the maps, scans were cross-correlated with a first-iteration map and then assigned a new timing offset. The

²⁰ We use standard ALMA calibrators from the GridCal program. See http://www.alma.cl/~ahales/cal_survey/plots/calsurvey_monitoring_B3.html and https://almascience.eso.org/sc/.
²¹ https://github.com/sievers/minkasi
**Figure 1.** MUSTANG-2 image of the G01 field, centered on Sgr B2.

**Figure 2.** MUSTANG-2 image of the G12 field, including the W33 star-forming region.

**Figure 3.** MUSTANG-2 image of the G29 field.

**Figure 4.** MUSTANG-2 image of the G31 field containing W43.

**Figure 5.** MUSTANG-2 image of the G34 field. Above $b \gtrsim 0$ deg, horizontal cross scans have not been obtained; the vertical streak seen at $\ell = 34.25$ deg is a consequence of these missing data.

**Figure 6.** MUSTANG-2 image of the G43 field, which contains the W49A star-forming complex (center) and the W49B supernova remnant (just southeast of the center).
timing errors ranged from $\sim$10 to 30 ms, corresponding to angular scales of $\approx$1$''$–3$''$ at our scan rate of $\approx$90 arcsec s$^{-1}$ (scan speeds vary during an observation). Additional half-beam timing-related pointing errors were noted in some individual scans, resulting in additional streaking artifacts in the data. Most of these issues disappeared after smoothing the data with some individual scans, resulting in additional streaking artifacts in the data.

We compared the MUSTANG-2 maps with 20 cm images from the Multi-Array Galactic Plane Imaging Survey (MAGPIS; Helfand et al. 2006) and from other sources (Mehringer 1994; Yusef-Zadeh et al. 2004) to measure pointing offsets, since these images showed the closest morphological match to the MGPS90 data. However, there are substantial regions in each field, particularly the Galactic center, that are synchrotron-dominated at 20 cm and have no corresponding features at 3 mm; we masked out these features. We use the image-registration$^{22}$ toolkit to cross-correlate the MUSTANG-2 images with the 20 cm images and use a Fourier-domain upsampling approach to obtain sub-pixel positional offsets. We were not able to measure statistical uncertainties on these offsets, but correcting the images for the offsets resulted in smaller visual residuals in the difference images shown in Section 4. The measured offsets are reported in Table 2 and show the offset of the 20 cm data with respect to the MUSTANG-2 data. The mean and standard deviation offset from the 20 cm data are $\Delta l = 1.88 \pm 2.6$ and $\Delta b = 4.4 \pm 2.7$, respectively.

In several cases, the measured offset is comparable to the MUSTANG-2 beam. We therefore correct these images for the offset, assuming the Very Large Array (VLA) 20 cm data have the correct pointing. The original pointing centers are recorded in the FITS headers of the published images with names CRVALnA so that the original pointing centers can be used if needed.

### 2.5. Effective Central Frequency

The MUSTANG-2 bandpass filter is approximately flat over the range of 75–105 GHz; though, including surface inaccuracies.

#### Table 3

| $\alpha$ | Frequency (GHz) | Wavelength (mm) |
|---------|-----------------|-----------------|
| 0.0     | 87.85 GHz       | 3.413 mm        |
| 0.5     | 88.23 GHz       | 3.398 mm        |
| 1.0     | 88.62 GHz       | 3.383 mm        |
| 1.5     | 89.02 GHz       | 3.368 mm        |
| 2.0     | 89.41 GHz       | 3.353 mm        |
| 2.5     | 89.80 GHz       | 3.338 mm        |
| 3.0     | 90.19 GHz       | 3.324 mm        |
| 3.5     | 90.58 GHz       | 3.310 mm        |
| 4.0     | 90.96 GHz       | 3.296 mm        |

Note. The central frequencies are computed by integrating the first moment of a power-law source function of $S(\nu) = \nu^\alpha$ over the MUSTANG-2 bandpass including the effect of surface errors using the Ruze formula with an rms surface accuracy of 230 $\mu$m (Frayer et al. 2018).

### 2.6. Combination with Planck Data

The largest angular scale recovered by the MUSTANG-2 data pipeline is approximately 4/25. Large angular scale structure is therefore missing. To recover those missing scales, we combine the MUSTANG-2 data with Planck 100 GHz data (with an effective central frequency of 104.225 GHz, assuming a spectral index $\alpha = 3$) scaled to an adopted central frequency of 90.19 GHz for MUSTANG-2, as appropriate for $\alpha = 3$ (see Section 2.5). We use a simple feather procedure (Cotton 2017) as implemented in the uvcombine$^{23}$ python package. Planck’s spatial resolution is $\approx$10$'$, which is substantially larger than the largest scale recovered in the MGPS90 data, so intermediate-scale structures (4$'$–10$'$) are likely recovered poorly. These data are not used in the analysis in this paper, but the FITS images are provided in the data repository.

### 3. Compact Source Catalogs

We use astrodendro$^{24}$ via the dendrocat$^{25}$ wrapper to extract a catalog of compact structures. In brief, astrodendro catalogs a hierarchically nested signal, effectively cataloging contoured regions. For the catalog described here, we included only the most compact structures, which are the “leaves” in the catalog hierarchy.

To select primarily robust compact sources, we filter the images to reject scales $>45''$ prior to cataloging. We use a 4$\sigma$ flux threshold and a minimum of 100 pixels as the dendrogram parameters; the pixel scale is 1$''$/pixel, so our minimum object size is $\sim$1/2 of beam area. We then reject sources with a peak signal-to-noise ratio (S/N) less than 5, where we use the average noise level across the field. We report the noise level

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22 http://image-registration.rtfd.org
23 https://github.com/radio-astro-tools/uvcombine
24 https://dendrograms.readthedocs.io/en/stable/
25 https://dendrocat.readthedocs.io/en/latest/
estimated using the median absolute deviation scaled to the standard deviation for each field in Table 1.

The resulting catalog includes all of the significant pointlike sources in each field of view. However, this catalog also includes components of extended emission that had peaks that met the threshold criteria but are not distinct sources. The extended objects are a particularly prominent component of the Galactic center field.

To eliminate some of the extended structures, we then fit Gaussian profiles to each of the dendrogram-identified sources using the gaussfit_catalog package. Profiles were fitted to the original, unfiltered data. Profiles were restricted to have major and minor axes FWHM < 27″, restricting the fits to be within a factor of three of the beam size. Sources substantially larger than this likely have measured integrated intensities attenuated by the filter function of the data acquisition and reduction pipeline; however, the full spatial transfer function of MUSTANG-2 has not yet been measured. Fits were performed to a 30″ radius around each source. If a second source was present in that radius, it was masked out with a single-beam-FWHM circle.

A total of 709 sources were identified across the seven fields. Of these, the majority, 385, were extended and round ($\sigma_{\text{maj}} > 14''$), and an additional 251 had both long aspect ratios $\sigma_{\text{maj}}/\sigma_{\text{min}} > 1.5$ and were extended ($\sigma_{\text{maj}} > 14''$). Only 73 sources were compact ($\sigma_{\text{maj}} < 14''$). Note that any confused or clustered sources, e.g., two compact sources within $\sim 5''-20''$ of one another, would likely be classified as extended.

The full catalog is available on the project source code repository. A complete description of the catalog columns and an excerpt from the catalog are both shown in Appendix B.

### 3.1. Catalog Crossmatching

We crossmatch the resulting catalog with the catalogs listed in Table 4. Matches in these catalogs are included if there is a source within $10''$ (approximately the MUSTANG-2 beam FWHM) of the MGPS catalog entry.

Of the 709 total MGPS90 sources, 279 passed our selection criteria that the S/N in the source was S/N > 5 and the peak signal was at least twice that of the background, $S_{\text{peak}} > 2 S_{\text{background}}$. Of those, 240 had millimeter/submillimeter matches (Herschel 70–500 μm, LABOCA 870 μm, or Bolocam 1.1 mm), 119 had centimeter-wavelength matches (6 cm or 20 cm), and 34 had no match in the millimeter or centimeter catalogs. There were 126 sources crossmatched at shorter wavelengths but not at longer wavelengths, and 5 with long-wavelength matches but no short-wavelength.

Figure 8 shows the histogram of MUSTANG-2-measured fluxes in the catalog. Because the typical noise level was $\sim 1$ mJy, the catalog has few sources below 5 mJy. The overlaid histogram shows the subset of the sample with no detections at other wavelengths; this subset is much fainter than the overall distribution, suggesting that the majority of these sources were either below the detection limit or the confusion limit of the other surveys.

### 3.2. HCH II Region Identification

One of the aims of this survey is to identify the youngest high-mass protostars. Candidates are those sources with little to no mid-infrared emission and very compact, optically thick (hypercompact) H II regions.

Massive stars form in the middle of ultra-dense cores undergoing gravitational collapse, leading to an accretion rate of the order of $M \sim 10^{-3} M_{\odot}$ yr$^{-1}$ such that a 100 $M_{\odot}$ star takes about $10^5$ yr to accrete its mass. As the star contracts onto the main sequence, it starts to ionize its environment to create an HCH II region. For a sufficiently dense accretion flow, the
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Strömgren radius of the HCH II region is bound by the gravity of the star, with a radius of \( R_G \sim 50–100 \text{ au} \) (Keto 2002, 2003, 2007). Such gravitationally bound HCH II regions are optically thick at centimeter wavelengths and therefore emit as blackbodies at wavelengths \( \lambda \gtrsim 3 \text{ mm} \), with

\[
S_\nu = 21 \text{ mJy} \left( \frac{d}{5 \text{ kpc}} \right)^2 \left( \frac{R}{100 \text{ au}} \right)^2 \left( \frac{\nu}{90 \text{ GHz}} \right)^2,
\]

which is only 0.06 mJy at \( \nu = 5 \text{ GHz} \) and is therefore below the detection limit of many existing surveys; they are certainly unremarkable sources at long wavelengths. HCH II regions can be distinguished from older ultracompact (UCH II) regions by their bright 90 GHz emission and faint emission at 5 GHz or lower frequencies. Sources with free–free emission that peaks at or is just below 3 mm represent the youngest high-mass young stellar objects (YSOs). The dense cores surrounding these sources will be bright in the millimeter regime, since they will have high dust column densities and temperatures.

We therefore select candidate HCH II regions as those fitting either of these criteria:

1. \( S_{3 \text{ mm}} > 1.75 S_{0 \text{ cm}} \). This requirement selects free–free sources that have \( \tau_{\text{ff}} = 1 \) at \( \lambda = 6 \text{ cm} \). It corresponds to an emission measure of \( EM = 7 \times 10^7 \text{ cm}^{-6} \text{ pc} \).
2. The source is not detected at 6 and 20 cm, is detected at 1.1 mm, and has

\[
\frac{S_{3 \text{ mm}}}{S_{1.1 \text{ mm}}} > \left( \frac{3.28 \text{ mm}}{1.11 \text{ mm}} \right)^{-\alpha} = 0.039
\]

where \( \alpha = 3 \) is the spectral index for optically thin dust with an opacity index of \( \beta = 1 \). This requirement selects dust-detected sources in which there is some indication of an excess of free–free emission over pure dust emission at 3 mm. HCH II regions that are optically thick up to \( \sim 3 \text{ mm} \), those that are extremely compact and dense, are below the detection threshold of the centimeter surveys (\( \approx 2.5 \text{ mJy at 6 cm} \); Giveon et al. 2005a; Hoare et al. 2012).

These criteria provide a small sample of five candidate HCH II regions across the seven target regions. Only two of these candidates were morphologically compact. This sample consists of known ultracompact or HCH II region clusters (three are parts of W49A, which contains 12 sources that can be classified as HCH II regions; De Pree et al. 1997), the HCH II region G34.257+0.153, and the OH/IR star G30.944+0.035 (Wilson & Barrett 1972). The 10 known HCH II regions in W51 (Ginsburg et al. 2016a) were not recovered because they are blended, in the 9" MUSTANG-2 beams, with more diffuse H II regions.

However, the majority of sources in our catalog do not have centimeter-wavelength detections and therefore were not eligible to be selected based on criterion 1 above. The BGPS 1.1 mm data, which have only 30\(^{\prime}\) resolution, could be affected by confusion (source blending) and therefore be too bright for a 3 mm excess to be detected, preventing selection by criterion 2.

While we would expect some free–free excess at 90 GHz above the dust emission extrapolated from 1.1 mm in dusty HCH II regions, it is plausible that the excess is not enough to modify the spectral index to meet our selection criterion 2. Sources that have millimeter detections (since they must be surrounded by gas and dust) and not centimeter detections therefore remain candidate HCH II regions. This large sample of 126 additional candidates, especially the 10 that are compact, are interesting candidates for future deep centimeter observations.

Several well-known HCH II regions were excluded from these selection criteria. The HCH II regions in W51, including the W51e cluster and W51d2 (Ginsburg et al. 2016b), those in W49 (De Pree et al. 1997), and those in Sgr B2 (De Pree et al. 1998) are confused, residing in the same beams as other high-mass stars at different evolutionary states. G34.257+0.153 includes a pair of HCH II regions but less other surrounding emission, so it did pass our selection criteria (Sewilo et al. 2004; Avalos et al. 2006). MGPS90 is clearly capable of detecting HCH II regions that are not in dense protoclusters.

3.3. Constraints on HCH II Lifetimes

To estimate the relative lifetime of the hypercompact and ultracompact phases, we compare the number of HCH II candidates to the number of detected UCH II regions from the Co-Ordinated Radio "N" Infrared Survey for High-mass star formation (CORNISH) survey (Kalcheva et al. 2018). Wood & Churchwell (1989b) seeded the idea that UCH II lifetimes may be substantially longer than expected for a freely expanding Strömgren sphere of \( t_{\text{str}} \sim 4 \times 10^4 \text{ yr} \), but the improved sample of Kalcheva et al. (2018) suggests that the discrepancy is not so large. In any case, we adopt a loosely estimated UCH II lifetime within the range of \( 4 \times 10^4 \text{ yr} < t_{\text{UCH}} < 4 \times 10^5 \text{ yr} \).

In the observed regions, the CORNISH survey detected 73 UCH II regions. Over the same area, our sample includes 10 compact MUSTANG-2 sources with no centimeter detections, which are our additional candidates from Section 3.2, and four previously known HCH II regions. W51 contains 10 and W49A contains up to 12 additional HCH II region candidates when viewed at a high resolution (De Pree et al. 1997; Ginsburg et al. 2016b). The inferred lifetime of HCH II regions, using a sample size of 12–34 HCH II’s in the MGPS90 fields, is therefore 16%–46% that of UCH II regions, or \( 6 \times 10^3 \text{ yr} < t_{\text{HCH}} < 2 \times 10^5 \text{ yr} \). A more complete assessment from the larger survey may more tightly constrain these values.

![Figure 8. Histogram of the source catalog. Blue shows all sources, while orange (overlaid as a foreground layer) shows only those sources that have no matches at cm or mm wavelengths in the searched surveys.](image-url)
Furthermore, though, the relatively small number of new candidates (only 10) compared to the large numbers in compact regions suggests that HCHII regions form primarily in, or live longest in, clustered regions. This high production of HCHII regions in dense protoclusters can be either because more high-mass stars form there, indicating an overall higher population, or because the gas density is higher, allowing the HII regions to remain in the hypercompact phase for a longer period before expanding into UCHII or diffuse HII regions.

3.4. Representative SEDs of Selected Sources

To put the MGPS90 data in context, we show a few examples of SEDs extracted from the catalogs described in Section 3.1 along with cutout images extracted from the same surveys. The SEDs include the catalog-reported flux values from each of the crossmatched surveys and the dendrogram source flux for MUSTANG. The selected SEDs are of a probable planetary nebula (Figure 9), which exhibits emission at all wavelengths and was detected in extended Hα emission (Sabin et al. 2014), an OH/IR star (Figure 10) that is infrared- and millimeter-bright but is not detected at centimeter wavelengths, a high-mass YSO that is a candidate HCHII region with no centimeter detection (Figure 11), and a source containing a known pair of HCHII regions (Figure 12). These SEDs highlight the important role of MGPS90 data in bridging the gap between the millimeter and centimeter regimes.

4. Diffuse Emission: Free–Free Separation

As stated in the introduction, the MGPS90 data have contributions from thermal free–free, thermal dust continuum, and nonthermal synchrotron emission. We describe here our decomposition of the MGPS90 data into free–free and dust emission; the nonthermal emission was not separated from the free–free emission.

We use the APEX Telescope Large Area Survey of the Galaxy (ATLASGAL) 870 μm data (Schuller et al. 2009) to estimate the dust contribution since at 870 μm essentially all emission is from dust. We estimate the 90 GHz flux density from dust by scaling the ATLASGAL data assuming a dust emissivity index of $\beta = 1.5$. Using this value of $\beta$, the
ATLASGAL 870 \mu m and MGPS90 data flux densities are related via \( S_{90 \text{GHz}} \approx 0.013 S_{870 \mu m} \) (see Equation (1)). Values of \( \beta \) ranging from \( 1 < \beta < 2 \) are often inferred from SED modeling, so there is substantial (factor of \( \sim 4 \)) uncertainty in the extrapolated dust fluxes. While this uncertainty limits our ability to quantitatively interpret the dust-subtracted images, the morphology of these images is less affected. We subtract the scaled ATLASGAL data from an appropriately smoothed version of the MGPS90 map to obtain an estimated free–free map. We perform this subtraction on the feathered MGPS90 and Planck data (Section 2.6).

Similarly, we use 20 cm maps to estimate the dust contribution by subtracting a scaled 20 cm map from the MGPS90 data. For most fields, we use 20 cm MAGPIS data (Helfand et al. 2006), which has an angular resolution of \( \sim 6'' \) and a point source sensitivity of 1–2 mJy. MAGPIS does not cover the Galactic center or \( \ell > 48^\circ \), and so we use other data in these zones. In the Galactic center, we use the multi-configuration 20 cm map from Yusef-Zadeh et al. (2004, resolution \( \sim 30'' \)), and in the W51 field, we use the multi-configuration map from Mehringer (1994, resolution \( \lesssim 1'' \)). We scale the 20 cm to 90 GHz assuming the 20 cm consists exclusively of optically thin free–free emission following a power law of \( S_{\nu} \propto \nu^{-0.12} \) (Wilson et al. 2009). The observed fields were selected based on their rich ongoing star formation activity, so this approximation is reasonable, but there are several cases where additional emission mechanisms (e.g., synchrotron) contribute to the observed intensity.

We show the results of the decomposition for one example field in Figure 13; the rest of the MGPS90 fields are in the Appendix. Figure 13 contains panels of the MGPS90 data, the contribution to the MGPS90 data from thermal dust estimated from ATLASGAL subtraction, the contribution to the MGPS90 data from free–free and synchrotron emission, 20 cm data, and the contribution to the MGPS90 data from thermal dust estimated from 20 cm subtraction.

The example in Figure 13 shows good agreement between the two dust estimates and between the free–free estimates, and the differences highlight some of the incorrect assumptions in the above analysis. The excess diffuse emission in the rightmost panel (MGPS90—VLA) is most likely caused by

![Figure 10. SED of source G30.944+0.035, an OH/IR star. The dusty SED with no detected radio emission made this source a candidate hypercompact H II region based on the criteria in Section 3.2, though it only barely passed the second criterion.](image-url)
the VLA’s failure to recover large angular scales. The missing emission on the right side of that map is caused by the excess synchrotron emission in the Sgr A region, which is not accounted for in our simple free–free model. Both dust maps do well at recovering emission from the massive G0.253+0.015 cloud (the bean-shaped feature in the upper left) and the southern dust ridge (the prominent dust feature just below the center of the map).

The W43 region is substantially more dust-dominated than the Galactic Center (Figure 14). The dusty features, however, are all closely aligned with free–free features, so it is difficult to disentangle them by eye in the MGPS90 image. The MGPS90-20 cm image is negative in the 20 cm dominated regions, likely indicating that there is substantial nonthermal emission in these H II regions. While there are no known supernovae in the region, the population of OB and Wolf–Rayet stars powering the expanding H II region may also drive strong shocks into the surrounding medium (e.g., Bally et al. 2010), leading to nonthermal emission. The presence of such nonthermal emission indicates that electrons must be accelerated to relativistic velocities in the H II region, which has recently been shown to be possible in H II region expansion fronts (Padovani et al. 2019).

The W49B supernova remnant in the G43 field stands out as a bright nonthermal source. No other supernova remnants in the surveyed area are as bright at 3 mm (see Figure 6). Sun et al. (2011) found that the SED of W49B is well fit by a single power law from 200 MHz to 30 GHz with an index of $\alpha = -0.46 \pm 0.01$. They found that the 5 GHz integrated flux density is 19.10 ± 0.98 Jy, and the 90 GHz integrated flux density should be 5.1 Jy. Integrating over W9B, we find a flux density of 5.2 Jy, indicating that most of the associated emission is nonthermal.

The decomposed images are shown in Figures 13 and 14 and Appendix A.

We directly quantify the dust contribution to the 3 mm intensity in the targeted brightest fields. Each field includes one or more prominent extended structures that were the focus for
these pilot observations. For each of these structures, we extracted an area that encompasses the bulk of the 3 mm emission and measured the fraction of that emission that is explained by optically thin dust, which is the sum of the positive values from the scaled ATLASGAL data explained above divided by the sum of the 3 mm emission. The results are reported in Table 5. Because we have assumed $\beta = 1.5$, and typical dust $\beta$ values for the ISM are $\sim 1.5-2$ (e.g., Ossenkopf & Henning 1994), these can be treated as upper limits on the dust contribution.

In the regions of interest, the dust contribution at 3 mm is limited to $\lesssim 20\%$ on the several arcminute scales probed. Regions with substantial synchrotron contributions from supernova remnants (W49b and W51b) or other mechanisms (the Arches) have an even lower contribution from dust, $< 10\%$. In short, the integrated diffuse emission detected in MGPS90 is dominated by hot gas rather than from cold molecular gas. We are, however, unable to determine whether the area of the survey is dominated by hot or cold gas, as the large angular scale filtering of the interferometric data sets prevents such an assessment; it remains possible that the area (and volume) of the surveyed regions is dominated by cold dust emission, while the received flux is clearly dominated by hot gas.

5. Conclusions

We have presented the pilot data for the MUSTANG 90 GHz Galactic Plane Survey, MGPS90. When complete, this survey will cover most of the northern Galactic plane within $|b| < 0.5^\circ$. These initial data cover several high-mass star cluster forming regions. All imaged regions are dominated by free–free and synchrotron emission at 3 mm.

We cataloged emission in the images, identifying 279 sources using the dendrogram algorithm, of which 2 are verified HCH II regions, and another 10 are plausible candidates.
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Appendix A

Additional Free–Free/Dust Decomposition Maps

In this appendix, we show cutout images focused on a selection of bright extended emission regions and the associated free–free decomposition described in Section 4. These are Figures A1–A7.
Figure A1. Decomposition of the MGPS90 data in the G01 field centered on Sgr B2. See Figure 13 for a description of the panels. The differences in the ATLASGAL and 20 cm based dust decomposition highlight the different angular scales recovered by those data sets.

Figure A2. Decomposition of the MGPS90 data in the G12 field centered on W33. See Figure 13 for a description of the panels. The diffuse free–free emission is well-removed by subtracting the 20 cm data, but the compact point source appears much brighter in the 3 mm derived map; this difference is likely because free–free emission is present but optically thick at 20 cm, resulting in an underestimate of the free–free contribution at 3 mm.

Figure A3. Decomposition of the MGPS90 data in the G29 field. See Figure 13 for a description of the panels. Some of the compact structures exhibit strong excesses at 20 cm.

Figure A4. Decomposition of the MGPS90 data in the G34 field centered on G34.26+0.15. See Figure 13 for a description of the panels. The vertical streak is an artifact as mentioned in Figure 5.
Appendix B
Catalog

Table B1 shows an excerpt from the catalog including the brightest 20 sources. The full catalog is available in the machine-readable version of the table. We include the dendrogram measurements of the integrated flux density and the Galactic $\ell$ and $b$ centroids, integrated flux densities in 10″ and 15″ apertures, the median background in a 15″–20″ aperture, and the parameters of the best-fit two-dimensional Gaussian profile. The sample table is sorted by the Gaussian peak amplitude ($A_G$) in descending order.

Figure A5. Decomposition of the MGPS90 data in the G43 field centered on W49A. See Figure 13 for a description of the panels. As in Figure A3, several compact structures appear to have excess 20 cm emission. However, other structures exhibit free–free emission that is optically thick at 20 cm and is therefore undersubtracted at 3 mm in panel (d); see also Figure A7.

Figure A6. Decomposition of the MGPS90 data in the G43 field centered on W49B. See Figure 13 for a description of the panels. W49B is a supernova remnant completely dominated by synchrotron emission. Panel (b) therefore shows synchrotron, not free–free, emission.

Figure A7. Decomposition of the MGPS90 data in the G49 field centered on W51 Main. See Figure 13 for a description of the panels. There is a mix of under- and oversubtracted emission in the dust map in panel (d); the arc shape in the center is purely free–free emission (Ginsburg et al. 2016b, 2017), but it is optically thick at 20 cm.
### Table B1

**MUSTANG-2 Source IDs and Photometry**

| ID   | Dendrogram $S_\nu$ (Jy) | $\ell$ (°) | $b$ (°) | $S_{\nu,10''}$ (Jy) | $S_{\nu,15''}$ (Jy) | $S_{\nu,15''-20''}$ (Jy beam$^{-1}$) | $A_G$ (Jy beam$^{-1}$) | $\ell_G$ (°) | $b_G$ (°) | FWHM$_{maj,G}$ (°) | FWHM$_{min,G}$ (°) | PA$_G$ (°) |
|------|-------------------------|------------|--------|----------------------|----------------------|----------------------------------------|------------------------|-------------|--------|------------------|------------------|-----------|
| 35.00| 17.01                   | 12.805     | −0.201 | 3.657                | 6.887                | 2.292                                  | 5.80                   | 12.806      | −0.201 | 17.034           | 14.966           | 90        |
| 56.00| 8.30                    | 43.167     | 0.010  | 3.099                | 5.49                 | 1.564                                  | 5.22                   | 43.167      | 0.010  | 15.685           | 11.546           | 76.062    |
| 166.00| 12.58                  | 0.668      | −0.035 | 2.699                | 5.067                | 1.846                                  | 3.94                   | 0.668       | −0.036 | 16.34            | 15.036           | 343.275   |
| 14.00| 4.88                    | 34.257     | 0.153  | 2.333                | 3.728                | 0.592                                  | 4.56                   | 34.257      | 0.153  | 11.208           | 9.439            | 67.04     |
| 66.00| 6.43                    | 49.492     | −0.368 | 2.071                | 3.644                | 1.059                                  | 3.10                   | 49.492      | −0.368 | 16.674           | 13.335           | 132.052   |
| 49.00| 11.59                   | 49.489     | −0.380 | 1.698                | 3.408                | 1.481                                  | 2.06                   | 49.488      | −0.380 | 21.262           | 14.499           | 141.889   |
| 42.00| 4.67                    | 43.166     | −0.030 | 1.394                | 2.501                | 0.773                                  | 2.33                   | 43.166      | −0.030 | 13.947           | 13.589           | 360       |
| 142.00| 4.16                 | 359.946    | −0.046 | 0.853                | 1.604                | 0.624                                  | 1.42                   | 359.946     | −0.046 | 14.779           | 14.363           | 360       |
| 116.00| 2.70                   | 29.957     | −0.017 | 0.766                | 1.451                | 0.409                                  | 1.37                   | 29.956      | −0.017 | 14.89            | 12.647           | 65.432    |
| 36.00| 0.95                    | 12.813     | −0.199 | 0.692                | 1.19                 | 0.345                                  | 1.15                   | 12.812      | −0.199 | 27.0             | 21.545           | 360       |
| 41.00| 2.64                    | 29.957     | −0.018 | 0.653                | 1.204                | 0.402                                  | 1.06                   | 29.957      | −0.018 | 15.584           | 14.434           | 0         |
| 45.00| 1.40                    | 49.491     | −0.386 | 0.602                | 1.175                | 0.428                                  | 0.74                   | 49.491      | −0.386 | 27.0             | 19.286           | 256.306   |
| 51.00| 0.69                    | 43.172     | −0.001 | 0.448                | 0.82                 | 0.251                                  | 0.70                   | 43.172      | −0.000 | 16.815           | 15.165           | 360       |
| 179.00| 1.32                  | 31.412     | 0.308  | 0.374                | 0.696                | 0.201                                  | 0.61                   | 31.412      | 0.307  | 15.161           | 13.027           | 121.242   |
| 164.00| 0.83                  | 30.866     | 0.114  | 0.372                | 0.593                | 0.101                                  | 0.69                   | 30.866      | 0.114  | 11.418           | 10.267           | 129.634   |
| 62.00| 0.93                    | 30.720     | −0.083 | 0.362                | 0.617                | 0.136                                  | 0.68                   | 30.720      | −0.083 | 12.342           | 11.126           | 130.278   |
| 55.00| 1.85                    | 43.149     | 0.012  | 0.326                | 0.623                | 0.241                                  | 0.73                   | 43.148      | 0.013  | 19.1             | 13.303           | 0         |
| 156.00| 0.57                   | 0.658      | −0.042 | 0.261                | 0.447                | 0.109                                  | 0.48                   | 0.659       | −0.041 | 27.0             | 13.659           | 135.233   |
| 133.00| 0.90                   | 30.534     | 0.021  | 0.248                | 0.446                | 0.132                                  | 0.41                   | 30.534      | 0.021  | 12.704           | 15.0774          | 0         |

**Note.** The subscripts $X_G$ are for the parameters derived from Gaussian fits. The values displayed are rounded such that the error is in the last digit; error estimates can be found in the machine-readable version of the table. Note that position angles in the set (0, 90, 180, 270, and 360) are caused by bad fits. These fits are kept in the catalog because they passed other criteria and are high signal to noise, but they are likely of sources in crowded regions so the corresponding fit parameters should be treated with caution.

(This table is available in its entirety in machine-readable form.)
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