THE GREEN BANK TELESCOPE MAPS THE DENSE, STAR-FORMING GAS IN THE NEARBY STARBURST GALAXY M82

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ABSTRACT

Observations of the Milky Way and nearby galaxies show that dense molecular gas correlates with recent star formation, suggesting that the formation of this gas phase may help regulate star formation. A key test of this idea requires wide-area, high-resolution maps of dense molecular gas in galaxies to explore how local physical conditions drive dense gas formation, but these observations have been limited because of the faintness of dense gas tracers like HCN and HCO+. Here we demonstrate the power of the Robert C. Byrd Green Bank Telescope (GBT)—the largest single-dish millimeter radio telescope—for mapping dense gas in galaxies by presenting the most sensitive maps yet of HCN and HCO+ in the starburst galaxy M82. The HCN and HCO+ in the disk of this galaxy correlates with both recent star formation and more diffuse molecular gas and shows kinematics consistent with a rotating torus. The HCO+ emission extending to the north and south of the disk is coincident with the outflow previously identified in CO and traces the eastern edge of the hot outflowing gas. The central starburst region has a higher ratio of star formation to dense gas than the outer regions, pointing to the starburst as a key driver of this relationship. These results establish that the GBT can efficiently map the dense molecular gas at 90 GHz in nearby galaxies, a capability that will increase further with the 16 element feed array under construction.

Key words: galaxies: individual (M82) – galaxies: ISM – galaxies: starburst – galaxies: star formation – ISM: molecules – radio lines: ISM

1. INTRODUCTION

Observations of local Milky Way clouds show that the bulk of molecular gas is inert with star formation concentrated in the small fraction of the cloud at high surface density (Heiderman et al. 2010; Lada et al. 2010, 2012). This observation leads to the idea that the “dense” molecular gas (AV ≳ 10 mag, n(H2) ≳ 10^4 cm^-3), rather than the whole molecular interstellar medium (AV ≳ 1 mag, n(H2) ≳ 10^2 cm^-3), represents the star-forming phase.

Extragalactic scaling relations also support the idea that the amount of high density molecular gas helps to set the star formation rate. Low angular resolution spectroscopy of nearby galaxies reveal a constant ratio (within a factor of a few) of HCN intensity, which traces the rate of recent star formation, across a wide range of systems, including the central parts of nearby disks, starbursts, and major mergers (Gao & Solomon 2004b; Juneau et al. 2009; García-Burillo et al. 2012). Surprisingly, the HCN-to-IR ratios for whole galaxies are comparable to those in local cloud cores (Wu et al. 2010), implying a constant ratio of dense gas to star formation rate. The ratios of CO intensity, which trace the overall molecular gas mass, to the IR emission, however, vary by more than a factor of 10 between disk and starburst galaxies, suggesting that in extreme regions the relationship between the total molecular gas mass and the amount of star formation may be non-linear (Gao & Solomon 2004b; Leroy et al. 2013; Carilli & Walter 2013).

If the amount of dense gas is linked to the amount of star formation, then the formation of dense gas from more diffuse molecular gas represents an important regulating process. While there may be many regulating steps (e.g., the formation of giant molecular clouds out of diffuse H2, accretion onto the galaxy), there are many obstacles to pursuing systematic studies of the HCN-to-CO ratio, or analogous measures of the dense gas fraction like the HCO+-to-CO ratio, within the line emission: averaged over a large part of a galaxy, the HCN and HCO+ lines are 10–30 times fainter than CO (Gao & Solomon 2004b). A result, most studies of extragalactic dense gas with small-aperture millimeter-wave telescopes have focused on individual deep pointings rather than wide-field maps. The new SETI (“W band”) heterodyne receiver on the Robert C. Byrd Green Bank Telescope (GBT) has the potential to extend these single-pointing observations and map HCN and HCO+ distributions in nearby galaxies because of the GBT’s large collecting area, high surface accuracy, and good resolution.

In this Letter, we demonstrate the power of the GBT as an HCN and HCO+ mapping machine for nearby galaxies using new GBT maps of HCN(J = 1–0) and HCO+(J = 1–0) in the nearby (D = 3.530 Mpc; Dalcanton et al. 2009) starburst...
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Table 1

| Summary of Observations |
|-------------------------|
|                        |
| UT Times               |
| 2013 March 9           |
| 3:15–11:15             |
| 3:45–6:45              |
| 2:00–5:45              |
| Number of spectral windows |
| 2                       |
| 2                       |
| 2                       |
| Bandwidth per window (MHz) |
| 200                      |
| 200                      |
| 200                      |
| Spectral resolution (kHz) |
| 244                      |
| 12.207                   |
| 12.207                   |
| Flux calibrator          |
| 0539+5507                |
| 1229+0203                |
| 1229+0203                |
| Flux calibrator flux (Jy) |
| 4.0                      |
| 8.5                      |
| 9.9                      |
| Pointing source          |
| 0841+7053                |
| 0841+7053                |
| 0841+7053                |
| Average opacity (e)      |
| 0.086                    |
| 0.109                    |
| 0.082                    |
| Average system temperature (HCN, HCO+) (K) |
| 109.117                  |
| 112.117                  |
| 89.88                    |
| Main beam efficiency (HCN, HCO+) |
| 0.26, 0.29               |
| 0.26, 0.30               |
| 0.23, 0.22               |

Notes.

a Values from the CARMA Calfind database (http://carma.astro.umd.edu/cgi-bin/calfind.cgi).

b At 103.5 GHz.

c At 92.6 GHz.

d From GBT High Frequency Weather Forecasts (http://www.gb.nrao.edu/~rmaddale/WeatherNAM/).

e The actuators for a section of panels were inoperational for this session leading to lower efficiencies.

2. GBT OBSERVATIONS

We used the newly commissioned 4mm (“W band”) receiver and the GBT Spectrometer to simultaneously map the HCN (J = 1–0) (νrest = 88.63160 GHz) and HCO+(J = 1–0) (νrest = 89.18853 GHz) intensity across the central 1.75 by 1.5 (1.8 x 1.5 kpc) of M82. Table 1 gives the details of the observations (GBT project 13A-253).

We used a single beam of the W-band receiver to make rapid maps, sampling 5 times each beam FHWM in the scanning direction and sampling 2.4 times each beam FHWM in the orthogonal direction (Mangum et al. 2007).

The observations were made over ~15 hr in excellent weather. Out-of-focus holography scans were made every two hours to correct the dish surface, pointing and focus checks were made every hour, and flux calibration observations were done every observing session. The receiver gain was calibrated using hot and cold loads. The “OFF” spectrum was created using every observing session. The receiver gain was calibrated using a mixture of free-free and synchrotron emission, which both trace the distribution of recent star formation. The total flux in the map agrees with the total flux measured from single dish observations in the literature.

3. RESULTS

The HCN and HCO+ maps demonstrate the GBT’s excellent capabilities for mapping large areas at high surface brightness sensitivity with good resolution (Figure 1). Higher resolution maps have been published for both HCN J = 1–0 (Brouillet & Schilke 1993) and HCO+ J = 1–0 (Seaquist et al. 1998), but the HCO+J = 2–1 resolution and covers a wide field. The HCO+J = 1–0 map has higher resolution (3.6′′), but covers a smaller field of view. We also compare our data to a new 3.0 GHz Jansky Very Large Array (VLA) continuum map (J. Marvil et al., 2013, in preparation; VLA/10C-199, VLA/12A-457, TDEM0010), which has 0.7 resolution and includes a mixture of free-free and synchrotron emission, which both trace the distribution of recent star formation. The total flux in the map agrees with the total flux measured from single dish observations in the literature.
Figure 1. Top and middle rows: the HCN (top) and HCO+ (middle) integrated line flux (moment zero) contours overlaid on a 3 GHz radio continuum image (J. Marvil et al. 2013, in preparation; left), an X-ray image with the point sources highlighted in pink (NASA/CXC/SAO/PSU/CMU; middle), and a $^{12}$CO(1–0) integrated flux image (Walter et al. 2002; right). The HCN and HCO+ emission are both correlated with the total molecular gas and star formation in the center of M82. The diffuse HCO+ emission on the northeastern edge of the disk correlates with the outflow seen in $^{12}$CO(1–0) by Walter et al. (2002) and outlines the eastern edge of the hot gas associated with the outflow seen in diffuse X-rays (Stevens et al. 2003). The contours start at 6σ and go up by factors of two ($1\sigma_{\text{HCN}} = 3.09$ K km s$^{-1}$ and $1\sigma_{\text{HCO+}} = 2.26$ K km s$^{-1}$). The magenta ellipse in the top left panel indicates the region from which the spectra in Figure 2 were extracted. Bottom row: the first moment map (mean velocity) for HCN, HCO+, and $^{12}$CO(1–0). Both velocity fields are consistent with a rotating torus of molecular material (Nakai et al. 1987; Shen & Lo 1995). The possibly outflowing HCO+ material north and south of the disk has velocities similar to the outflowing material in the center of M82 instead of velocities associated with the rotating molecular torus. The GBT, OVRO, and VLA beams are shown in the lower left corner of relevant panels and a $10''$ scale bar in the lower right hand corner of all panels.

3.1. HCN, HCO+, and CO comparison

The morphology of HCN and HCO+ emission follows the galaxy disk and coincides with the main ridge of $^{12}$CO(1–0) emission and the star formation traced by the radio continuum emission (top and middle panels of Figure 1). The velocity distributions of the disk HCN and HCO+ emission are similar to the velocity distribution of the CO disk (bottom panels of Figure 1), suggesting that the HCN, HCO+, and CO emission in the disk originates from the same rotating molecular torus (Nakai et al. 1987; Shen & Lo 1995).

For the first time, we also measure HCO+ emission at low surface brightness associated with the $^{12}$CO(1–0) emission extending north and south of the main disk (Walter et al. 2002). Simulations of the GBT beam shape at 4 mm indicate that this emission does not originate from sidelobes. The HCO+ emission outlines the eastern edge of the X-ray emission associated with the central outflow, suggesting that the dense molecular gas is entrained in the outflow of lower density gas. The HCO+ in this region also is kinematically inconsistent with a disk, similar to what is seen in CO (cf. Figure 6 in Walter et al. 2002 and Figure 1 here).

CO emission has been associated with the outflow in M82 (Walter et al. 2002) and has been seen in the outflow from the starburst nucleus of NGC 253 (Bolatto et al. 2013). Emission from HCN and HCO+ has also been associated with the active galactic nucleus driven outflow in the ULIRG Mrk 231 (Aalto et al. 2012). To our knowledge, the current observations, however, would be the first time that dense molecular gas, as traced by HCO+, has been found to be associated with a starburst-driven outflow in a nearby galaxy. The outflow of dense molecular gas seen in HCO+ may regulate star formation in galaxies like M82 by removing the fuel for star formation.

The disk-averaged line profiles of the HCN and HCO+ emission agree with $^{12}$CO(2–1) emission from the HERACLES image (Leroy et al. 2009; A. K. Leroy et al., in preparation) in Figure 2. Both HCN and HCO+ have structure near 220 km s$^{-1}$, which is not seen in $^{12}$CO(2–1) but is seen in the higher order CO transitions (Loenen et al. 2010). The models of the CO emission from Loenen et al. (2010) show that the different CO
transitions reflect different molecular gas densities. Transitions like $^{12}$CO(2–1) are emitted by relatively diffuse ($10^{3.5}$ cm$^{-3}$) molecular gas associated with the disk, while the higher order CO transitions ($J > 4$) are emitted by two denser components ($10^{5}$ cm$^{-3}$ and $10^{6}$ cm$^{-3}$) associated with the star-forming gas (Loenen et al. 2010). Inspection of the channel maps near 220 km s$^{-1}$ confirm that the lack of structure in the $^{12}$CO(2–1) is due to the presence of a significant amount of CO emission associated with the warm and diffuse molecular gas found throughout the disk, while the HCN and HCO$^+$ trace the denser molecular gas component found in the torus.

3.2. The Relationship between HCN, HCO$^+$, CO, and Star Formation

To explore the relationships between HCN, HCO$^+$, CO, and star formation within M82, we smoothed the images to the same resolution (9.2$''$), regridded them to the same coordinate system, and rebinned the pixels so that each pixel represents an independent sample. The line intensities were derived from moment zero maps and the luminosities were calculated by multiplying the intensities by the area of a pixel. Regions less than 3σ were blanked.

Figure 3 compares the distribution of $L_{CO}/L_{HCN}$, $L_{CO}/L_{HCO^+}$, and $L_{HCN}/L_{HCO^+}$ for regions within M82 and for entire galaxies (or centers of galaxies) from the literature (Gao & Solomon 2004b; Graciá-Carpio et al. 2008; Juneau et al. 2009; García-Burillo et al. 2012). In M82, the distributions of all three ratios have the same range as the points from the literature, although $L_{CO}/L_{HCN}$ and $L_{CO}/L_{HCO^+}$ do peak at lower values. However, we must be cautious because we are comparing measurements of entire galaxies with spatially resolved measurements within a galaxy. Because the CO emission has a larger filling factor than the HCN emission, the unresolved measurements may have systematically larger $L_{CO}/L_{HCN}$ and $L_{CO}/L_{HCO^+}$ ratios. The $L_{CO}/L_{HCN}$ and $L_{HCN}/L_{HCO^+}$ values for M82 as a whole are similar to the mode of the values found for other galaxies, while the $L_{CO}/L_{HCO^+}$ value is slightly lower. The $L_{CO}/L_{HCN}$ and $L_{CO}/L_{HCO^+}$ values increase with distance...
Figure 4. Top: the star formation rate traced by infrared luminosity as a function of the amount of dense gas traced by HCN (left) and HCO+ (right). The \( L_{\text{IR}} - L_{\text{HCN}} \) fit for a sample including both normal galaxies and LIRGs/ULIRGs from Gao & Solomon (2004a) is shown as a solid line; star-forming regions within the Milky Way also follow this fit (Wu et al. 2010; Ma et al. 2013). The dotted line shows the \( L_{\text{IR}} - L_{\text{HCN}} \) fit derived from the sample of LIRGs/ULIRGs (Graciá-Carpio et al. 2008; García-Burillo et al. 2012). The integrated \( L_{\text{IR}} \) and \( L_{\text{HCN}} \) points for M82 follow the LIRG/ULIRG relationship between \( L_{\text{IR}} \) and \( L_{\text{HCN}} \). Regions within M82, however, span a range of values with the high luminosity HCN and HCO+ points following the LIRG/ULIRG relationship and the low luminosity points following instead the relationship seen in normal galaxies and in the Milky Way. We see a similar trend for \( L_{\text{IR}} vs. L_{\text{HCO+}} \). Bottom: in M82, the amount of dense gas per total molecular gas mass (\( L_{\text{HCN}}/L_{\text{CO}} \) and \( L_{\text{HCO+}}/L_{\text{CO}} \)) and the amount of star formation per total molecular gas mass (\( L_{\text{IR}}/L_{\text{CO}} \)) are both high. The errors on the M82 data in all plots are smaller than the symbol size.

from the center of the galaxy (bottom panels of Figure 3), suggesting the fraction of dense gas decreases with distance from the center. The \( L_{\text{HCN}}/L_{\text{HCO+}} \) ratio is roughly constant across the center of the galaxy with higher values at the southern edge.

Figure 4 compares the relationship between the total molecular gas mass (\( L_{\text{CO}} \)), the dense gas mass (\( L_{\text{HCN}} \) and \( L_{\text{HCO+}} \)), and the star formation rate (\( L_{\text{IR}} \)) for the entire M82 disk, points within M82, the sample of galaxies from the literature used in Figure 3, and star-forming regions in the Milky Way (Wu et al. 2010; Ma et al. 2013). We have estimated \( L_{\text{IR}} \) for the M82 points by multiplying the 3.0 GHz continuum flux density per pixel by the ratio of the infrared luminosity to the 3 GHz flux density for the entire galaxy. In effect, this procedure relies on the radio-infrared correlation, one of the tightest astronomical correlations, but avoids additional systematic errors by using the empirical ratio rather than a fit to the correlation seen in a large sample of galaxies. The use of the 3 GHz radio continuum ameliorates the significant optical depth effects found in edge-on galaxies like M82.

For the entire M82 disk, the relationship between the \( L_{\text{IR}} \) and \( L_{\text{HCN}} \) values matches the trend between \( L_{\text{IR}} \) and \( L_{\text{HCN}} \) found for a sample of LIRGs and ULIRGs, which have high star formation rates. However, our data shows that the relationship between \( L_{\text{IR}} \) and \( L_{\text{HCN}} \) varies within M82. Regions away from the central starburst tend to have lower \( L_{\text{IR}} \) (star formation rate) for a given amount of \( L_{\text{HCN}} \) (dense molecular gas). These points match the trend seen in normal galaxies (Gao & Solomon 2004b) and individual star-forming regions in the Milky Way (Wu et al. 2010). For points near the central starburst, the \( L_{\text{IR}} \) (star formation rate) is higher for a given amount of \( L_{\text{HCN}} \) (dense
molecular gas), matching the trend seen for LIRG/ULIRGs. We see a similar trend for the HCO⁺ measurements. Compared to normal galaxies, individual regions in M82 tend to have higher dense gas fractions ($L_{\text{HCN}}/L_{\text{CO}}$ or $L_{\text{HCO⁺}}/L_{\text{CO}}$) and higher ratios of star formation to total molecular gas mass ($L_{\text{IR}}/L_{\text{CO}}$), but the dense gas fractions vary by a factor of 10.

These resolved observations of M82 show that the relationship between the amount of dense gas and star formation rate (as traced by the radio continuum) varies within a single galaxy. The key variable appears to be the central starburst, which could be using up or expelling the dense gas, affecting the gas tracer chemistry, and/or changing how star formation proceeds. Future resolved observations of HCN and HCO⁺ in star-forming regions in a variety of galactic environments will allow us to disentangle these possibilities and understand how the central starburst in M82 influences star formation.

4. SUMMARY

We have made the most sensitive map to date of the dense molecular gas in the starburst galaxy M82 using the largest single-dish millimeter-wave telescope in the world: the GBT. The HCN and HCO⁺ emission correlates with lower density molecular gas, traced by CO, and star formation, traced by radio continuum, and its kinematics are consistent with the previously proposed torus of molecular gas. We also detect low surface brightness HCO⁺ emission coincident with the base of the molecular gas outflow first detected in CO and tracing the edge of the hot outflowing gas seen in the X-ray. The $L_{\text{CO}}/L_{\text{HCN}}$, $L_{\text{CO}}/L_{\text{HCO⁺}}$, and $L_{\text{HCN}}/L_{\text{HCO⁺}}$ ratios are similar to those in other starburst galaxies. The first two ratios increase with distance from the central starburst, implying that the fraction of dense gas decreases with distance from the starburst.

The relationship between the dense molecular gas and star formation varies with distance from the central starburst. Near its center, there is a higher ratio of star formation to dense molecular gas, similar to the relationship seen for LIRGs and ULIRGs, but outside of the central starburst, the ratio of the star formation to dense molecular gas decreases, agreeing with the correlation seen in normal galaxies and the Milky Way.

These observations demonstrate the effectiveness of the GBT for mapping dense molecular gas in external galaxies. The already-exciting capabilities of the GBT will be increased further with the advent of the 16 element 4 mm feed array (ARGUS) being built for the GBT and will complement on-going efforts with ALMA.

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Facilities: GBT, VLA

REFERENCES

Aalto, S., García-Burillo, S., Muller, S., et al. 2012, A&A, 537, A44
Bolatto, A. D., Warren, S. R., Leroy, A. K., et al. 2013, Natur, 499, 450
Brouillet, N., & Schilke, P. 1993, A&A, 277, 381
Carilli, C. L., & Walter, F. 2013, ARA&A, 51, 105
Dalcanton, J. J., Williams, B. F., Seth, A. C., et al. 2009, ApJS, 183, 67
Fuente, A., García-Burillo, S., Usero, A., et al. 2008, A&A, 492, 675
Gao, Y., & Solomon, P. M. 2004a, ApJS, 152, 63
Gao, Y., & Solomon, P. M. 2004b, ApJ, 606, 271
García-Burillo, S., Usero, A., Alonso-Herrero, A., et al. 2012, A&A, 539, A8
Graciá-Carpio, J., García-Burillo, S., Planesas, P., Fuente, A., & Usero, A. 2008, A&A, 479, 703
Heiderman, A., Evans, N. J., II, Allen, L. E., Huard, T., & Heyer, M. 2010, ApJ, 723, 1019
Juneau, S., Narayanan, D. T., Moustakas, J., et al. 2009, ApJ, 707, 1217
Kainulainen, J., Beuther, H., Henning, T., & Plume, R. 2009, A&A, 508, L35
Krips, M., Neri, R., García-Burillo, S., et al. 2008, ApJ, 677, 262
Lada, C. J., Forbrich, J., Lombardi, M., & Alves, J. F. 2012, ApJ, 745, 190
Lada, C. J., Lombardi, M., & Alves, J. F. 2010, ApJ, 724, 687
Leroy, A. K., Walter, F., Bigiel, F., et al. 2009, AJ, 137, 4670
Leroy, A. K., Walter, F., Sandstrom, K., et al. 2013, AJ, 146, 19
Loenen, A. F., van der Werf, P. P., Güsten, R., et al. 2010, A&A, 521, L2
Ma, B., Tan, J. C., & Barnes, P. J. 2013, ApJ, 779, 79
Maddalena, R. J. 2010, Theoretical Ratio of Beam Efficiency to Aperture Efficiency, GBT Memo 276 (Green Bank, WV; National Radio Astronomy Observatory)
Mangum, J. G., Emerson, D. T., & Greisen, E. W. 2007, A&A, 474, 679
Nakai, N., Hayashi, M., Handa, T. et al. 1987, PASJ, 39, 685
Nguyen-Q-Rieu, Nakai, N., & Jackson, J. M. 1989, A&A, 220, 57
Rieke, G. H., Lebofsky, M. J., Thompson, R. I., Low, F. J., & Tokunaga, A. T. 1980, ApJ, 238, 24
Sceauquis, E. R., Frayer, D. T., & Bell, M. B. 1998, ApJ, 507, 745
Shen, J., & Lo, K. Y. 1995, ApJL, 445, L99
Stevens, I. R., Read, A. M., & Bravo-Guerrero, J. 2003, MNRAS, 343, L47
The Astropy Collaboration, Robitaille, T. P., Tollerud, E. J., et al. 2013, A&A, 558, A33
Walter, F., Weiss, A., & Scoville, N. 2002, ApJL, 580, L21
Wu, J., Evans, N. J., II, Shirley, Y. L., & Knez, C. 2010, ApJS, 188, 313