STAR FORMATION IN THE GIANT H II REGIONS OF M101

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ABSTRACT

The molecular components of three giant H II regions (NGC 5461, NGC 5462, and NGC 5471) in the galaxy M101 are investigated with new observations from single-dish telescopes (James Clerk Maxwell Telescope and the NRAO 12 m) and from the Owens Valley Radio Observatory millimeter array. Of the three H II regions, only NGC 5461 had previously been detected in CO emission. We calculate preliminary values for the molecular mass of the GMCs in NGC 5461 by assuming a CO-to-H\textsubscript{2} factor (X factor) and then comparing these values with the virial masses. We found that the appropriate X factor is 5 times smaller than the X factor in the Milky Way despite the lower metallicity of M101. We conclude that the data in this paper demonstrate for the first time that the value of X may decrease in regions with intense star formation. The molecular mass for the association of clouds in NGC 5461 is approximately \(3 \times 10^7\) \(M_\odot\) and is accompanied by 1–2 times as much atomic mass. The observed CO emission in NGC 5461 is an order of magnitude stronger than in NGC 5462, but it was not possible to detect molecular gas toward NGC 5471 with the James Clerk Maxwell Telescope. An even larger ratio of atomic to molecular gas in NGC 5471 was observed, which might be attributed to inefficient conversion of molecular to atomic gas. The masses of the individual clouds in NGC 5461, which are gravitationally bound, cover a range of (2–8) \(10^5\) \(M_\odot\), comparable with the masses of Galactic giant molecular clouds. Higher star-forming efficiencies, and not massive clouds, appear to be the prerequisite for the formation of the large number of stars whose radiation is required to produce the giant H II regions in M101.

Subject headings: galaxies: individual (M101) — galaxies: ISM — ISM: clouds — radio lines: ISM — stars: formation

1. INTRODUCTION

Giant H II regions are the most spectacular star-forming regions in normal galaxies and have been the object of many studies because of their brightness (Shields 1990). Examples of giant H II regions are found in galaxies of different brightness and morphology (e.g., Pellet 550 in M31, NGC 604 in M33, 30 Dor in the Large Magellanic Cloud, and NGC 5461 in M101). Especially impressive are the H II regions observed in M101, which is a relatively nearby Sc spiral galaxy at 7.4 \(\pm\) 0.6 Mpc (Kelson et al. 1996). NGC 5471, one of the giant H II regions in M101, is 2 orders of magnitude larger and brighter than W49, the largest H II region in the Milky Way. What is special about M101 that it produces such bright H II regions? One hypothesis is that these regions result from the unusual properties of the molecular gas from which the stars that ionize the gas originate (Kennicutt 1984). In this paper, we present data on the physical properties of the molecular gas in the giant H II regions of M101 and discuss the implications for the formation of giant H II regions.

To explain the presence of massive star formation in the clouds associated with the giant H II regions, Kenney, Scoville, & Wilson (1991) proposed that either the initial mass function is enhanced in massive stars or the gas is consumed more efficiently in these regions. The first idea has been investigated by Rosa & Benvenuti (1994) in a study of four

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are used to find the physical properties of the associations of GMCs. In § 6, we compare the gas masses and temperatures of the three giant H II regions. We discuss the effect of star formation on the interstellar medium in § 7 and present our conclusions in § 8.

2. OBSERVATIONS

2.1. JCMT Data and Analysis

Receiver A2, used to observe the \( ^{12}\text{CO} \ J = 2 \rightarrow 1 \) line, has an FWHM of 20′ and an efficiency of 0.80, which is a correction for the radiation lost because of forward scattering and spillover. Receivers B3i and B3 were both used to observe the \( ^{12}\text{CO} \ J = 3 \rightarrow 2 \) line; their beam sizes are 14″ and 13″, respectively, while their efficiencies are 0.70 and 0.75. All of the observations at the JCMT were obtained between 1995 January and 1997 February in position-switching mode. The typical single-sideband system temperatures were 300–400 K for A2, 800–1000 K for B3i, and 400–600 K for B3. To reduce the data, we used SPECX, which is a spectral data reduction code written by R. Padman (Cavendish Laboratory, Cambridge, England, UK) for JCMT data. Linear baselines were removed after all of the scans of the same position were averaged. The data were binned to a frequency resolution of 5 MHz (which corresponds to 6.5 km s\(^{-1}\) at 230 GHz, and to 4.35 km s\(^{-1}\) at 345 GHz) to achieve satisfactory noise levels.

Tables 1 and 2 present the observed integrated antenna temperature, \( \int T^*_A \ dv \), for various positions around each H II region, while Figure 1 shows the three spectra at the peak positions in NGC 5461 and NGC 5462. In addition, Tables 1 and 2 list the parameters obtained from a Gaussian fit to each of the spectra, where \( V_{\text{peak}} \) is the velocity for the maximum antenna temperature, \( T_{\text{peak}} \), and \( \Delta V \) is the velocity width at half-maximum antenna temperature. These velocity widths are typically 10%, so there could be a systematic error of 10% that is introduced from the flux calibration.


\[ \frac{12}{13}\text{CO} \ J = 2 \rightarrow 1 \text{ emission was detected at the } 7 \sigma \text{ level or better toward all of the 11 points around NGC 5461. The peak antenna temperatures ranged between 68 and 228 mK. Interestingly, the } \frac{12}{13}\text{CO} \ J = 3 \rightarrow 2 \text{(345 GHz) emission from three } (a, b, \text{ and } c) \text{ of the five central points observed in NGC 5461 was between 65% and 100% as strong as the emission seen in the } \frac{12}{13}\text{CO} \ J = 2 \rightarrow 1 \text{ spectra (Table 1).}

The strongest detections in NGC 5462 in both \( \frac{12}{13}\text{CO} \ J = 2 \rightarrow 1 \) and \( J = 3 \rightarrow 2 \) were for position \( g \) and not for \( a \), which coincides with the center of the region. Special care was taken so that four positions around NGC 5462 were observed in \( \frac{13}{12}\text{CO} \ J = 3 \rightarrow 2 \) in order to be convolved together so that they could be compared with the lower

| Table 1 | Spectral Line Parameters for NGC 5461 with JCMT Data |
|---------|-----------------------------------------------------|
| Source  | \( \Delta \alpha \) (arcsec) | \( \Delta \delta \) (arcsec) | \( \int T^*_A \ dv \) (K km s\(^{-1}\)) | \( V_{\text{peak}} \) (km s\(^{-1}\)) | \( \Delta V \) (km s\(^{-1}\)) | \( T_{\text{peak}} \) (mK) | Integration Time (s) |
|---------|----------------------------|-----------------------------|----------------------------|-----------------------------|----------------------------|-----------------------------|-----------------------------|
| \( ^{12}\text{CO} \ J = 2 \rightarrow 1 \) | | | | | | | |
| NGC 5461a...... | 0 | 0 | 5.8 ± 0.3 | 276 | 24 | 228 ± 11 | 3000 |
| NGC 5461b...... | 7 | 7 | 5.4 ± 0.3 | 277 | 24 | 206 ± 11 | 1800 |
| NGC 5461c...... | -7 | -7 | 5.3 ± 0.3 | 273 | 24 | 207 ± 10 | 1800 |
| NGC 5461d...... | -7 | -7 | 4.7 ± 0.4 | 275 | 23 | 181 ± 11 | 1800 |
| NGC 5461e...... | 7 | 7 | 2.1 ± 0.4 | 273 | 24 | 83 ± 9 | 1800 |
| NGC 5461f...... | -14 | -14 | 5.6 ± 0.3 | 272 | 25 | 212 ± 11 | 1650 |
| NGC 5461g...... | 14 | 14 | 3.5 ± 0.4 | 287 | 22 | 158 ± 12 | 1800 |
| NGC 5461h...... | -14 | 0 | 5.9 ± 0.3 | 274 | 26 | 217 ± 9 | 1800 |
| NGC 5461i...... | 14 | 14 | 1.7 ± 0.4 | 277 | 25 | 68 ± 10 | 1800 |
| NGC 5461j...... | 0 | 14 | 1.5 ± 0.4 | 280 | 17 | 79 ± 10 | 1800 |
| NGC 5461k...... | 0 | -14 | 5.3 ± 0.3 | 272 | 24 | 202 ± 11 | 1800 |
| \( ^{13}\text{CO} \ J = 3 \rightarrow 2 \) | | | | | | | |
| NGC 5461a...... | 0 | 0 | 4.1 ± 0.2 | 277 | 23 | 180 ± 12 | 7200 |
| NGC 5461b...... | 7 | 7 | 3.3 ± 0.3 | 281 | 20 | 140 ± 15 | 3000 |
| NGC 5461c...... | -7 | -7 | 5.7 ± 0.2 | 275 | 27 | 210 ± 17 | 3000 |
| NGC 5461d...... | -7 | 7 | <1.1 ± 0.3 | ... | ... | <51 ± 18 | 3000 |
| NGC 5461e...... | 7 | -7 | <1.1 ± 0.3 | ... | ... | <53 ± 24 | 3000 |
| \( ^{13}\text{CO} \ J = 2 \rightarrow 1 \) | | | | | | | |
| NGC 5461a...... | 0 | 0 | 0.49 ± 0.05 | 272 | 27.8 | 17 ± 4.0 | 10840 |

Note: The offsets are with respect to the center of NGC 5461: \( \alpha = 14^h01^m55^s.6 \) and \( \delta = 54°33'31''0 \). The quantity \( \int T^*_A \ dv \) is the integrated antenna temperature. The FWHM, \( \Delta V \), and the central velocity, \( V_{\text{peak}} \), for which the maximum antenna temperature value, \( T_{\text{peak}} \), occurred were calculated by fitting Gaussian lines to the spectra.
resolution $^{12}$CO $J = 2 \rightarrow 1$ data. Finally, it was possible to get a significant detection of $^{13}$CO $J = 2 \rightarrow 1$ toward NGC 5461a (Table 1), while the detection toward NGC 5462g is more questionable (Table 2).

To our surprise, there was no detection of $^{12}$CO $J = 2 \rightarrow 1$ toward NGC 5471, one of the brightest H II regions in M101. To calculate an upper limit for the integrated intensity only, the upper limit derived in this way for NGC 5471 is $0.70 \text{ K km s}^{-1}$ integrated over $40 \text{ km s}^{-1}$.

2.2. NRAO 12 Meter Telescope Data

On 1996 November 6, we used the NRAO 12 m telescope to observe NGC 5461, NGC 5462, and NGC 5471 in the rotational transition of $^{12}$CO $J = 1 \rightarrow 0$ (Table 3). The beam is large enough ($55''$) to encompass each of the three giant H II regions; the integration times were 60, 120, and 78 minutes for NGC 5461, NGC 5462, and NGC 5471, respectively. Each individual scan was 6 minutes. Typical system temperatures at 115 GHz were 350–400 K. The 256 channel 1 MHz (2.6 km s$^{-1}$) dual polarization filterbank was configured in series mode to gain a factor of $2^{1/2}$ in the noise level. The telescope software presents the data in units of corrected radiation temperature, $T_R$, as opposed to the corrected antenna temperature, $T_A^*$. The calibration was estimated to be about 15%.

The data were reduced with UniPOPS. Linear baselines were removed from two of the spectra (NGC 5461 and NGC 5471), while a polynomial baseline was removed from the spectrum of NGC 5462. The data were smoothed to a resolution of 10 km s$^{-1}$ (or 4 MHz at 115 GHz) to improve the S/N. The $^{12}$CO $J = 1 \rightarrow 0$ spectra are shown in Figure 2, and the integrated intensities are given in Table 3.

2.3. OVRO Millimeter-Wave Interferometer Data

NGC 5461 and NGC 5462 were observed with the OVRO millimeter-wave interferometer during 1996 Feb-

### Table 2

**Spectral Line Parameters for NGC 5462 with JCMT Data**

| Source       | $\Delta x$ (arcsec) | $\Delta y$ (arcsec) | $\int T_R^* dv$ (K km s$^{-1}$) | $V_{peak}$ (km s$^{-1}$) | $\Delta V$ (km s$^{-1}$) | $T_{peak}$ (mK) | Integration Time (s) |
|--------------|---------------------|---------------------|-------------------------------|--------------------------|------------------------|------------------|----------------------|
| $^{13}$CO $J = 2 \rightarrow 1$ |
| NGC 5462a    | 0                   | 0                   | $<0.10 \pm 0.10$              | ...                      | ...                    | $<6 \pm 8$       | 1800                 |
| NGC 5462b    | 0                   | 6                   | $0.51 \pm 0.20$              | 300                      | 17.6                   | $28 \pm 8$       | 1800                 |
| NGC 5462c    | 0                   | 0                   | $<0.69 \pm 0.20$              | ...                      | $<19 \pm 7$           | 1800             |
| NGC 5462d    | 6                   | 0                   | $0.49 \pm 0.10$              | 304                      | 17.3                   | $27 \pm 7$       | 1800                 |
| NGC 5462e    | 0                   | 0                   | $0.57 \pm 0.10$              | 299                      | 16.4                   | $32 \pm 7$       | 1800                 |
| NGC 5462f    | 6                   | 6                   | $<0.41 \pm 0.10$              | ...                      | ...                    | $<18 \pm 7$      | 1800                 |
| NGC 5462g    | 0                   | 12                  | $0.69 \pm 0.05$              | 292                      | 12.0                   | $53 \pm 7$       | 1800                 |

| $^{12}$CO $J = 3 \rightarrow 2$ |
|---------------------------------|
| NGC 5462a                      | 0                   | 0                   | $<0.45 \pm 0.4$              | ...                      | ...                    | $21 \pm 6$       | 4800                 |
| NGC 5462b                      | 0                   | 0                   | $0.20 \pm 0.4$              | 295                      | 12                     | $18 \pm 6$       | 4800                 |
| NGC 5462c                      | 0                   | 0                   | $0.56 \pm 0.4$              | 296                      | 23                     | $25 \pm 7$       | 4800                 |
| NGC 5462d                      | 6                   | 6                   | $<0.66 \pm 0.2$              | ...                      | ...                    | $<14 \pm 6$      | 6000                 |
| NGC 5462e                      | 0                   | 12                  | $1.13 \pm 0.2$              | 297                      | 22                     | $50 \pm 6$       | 6000                 |
| NGC 5462f                      | 6                   | 6                   | $<0.41 \pm 0.3$              | ...                      | ...                    | $<15 \pm 12$     | 1200                 |
| NGC 5462g                      | 0                   | 18                  | $1.00 \pm 0.3$              | 300                      | 27                     | $36 \pm 12$      | 1200                 |
| NGC 5462h                      | 6                   | 12                  | $<0.94 \pm 0.3$              | ...                      | ...                    | $<27 \pm 12$     | 1200                 |
| NGC 5462i                      | 6                   | 12                  | $<0.49 \pm 0.3$              | ...                      | ...                    | $<49 \pm 12$     | 1200                 |

| $^{13}$CO $J = 2 \rightarrow 1$ |
|---------------------------------|
| NGC 5462g                      | 0                   | 12                  | $0.10 \pm 0.01$              | 295                      | 6                      | $10 \pm 2.5$     | 15600                |

Note.—The offsets are with respect to the center of NGC 5462: $\alpha = 14^h02^m07^s.6$ and $\delta = 54^\circ36'17''4$. The quantity $\int T_R^* dv$ is the integrated antenna temperature. The FWHM, $\Delta V$, and the central velocity, $V_{peak}$, for which the maximum antenna temperature value, $T_{peak}$, occurred are calculated by fitting Gaussian lines to the spectra.

### Table 3

**$^{12}$CO $J = 1 \rightarrow 0$ Spectral Line Parameters for the NRAO Data**

| Source       | $\int T_R^* dv$ (K km s$^{-1}$) | $V_{peak}$ (km s$^{-1}$) | $\Delta V$ (FWHM) (km s$^{-1}$) | $T_{peak}$ (mK) |
|--------------|-----------------------------|--------------------------|-------------------------------|------------------|
| NGC 5461     | $2.50 \pm 0.48$            | 274                      | 29                            | $78 \pm 8$       |
| NGC 5462     | $0.38 \pm 0.11$            | 296                      | 30                            | $12 \pm 2$       |
| NGC 5471     | $<0.54 \pm 0.20$           | ...                      | ...                           | $<12 \pm 12$     |

Note.—The quantity $\int T_R^* dv$ is the integrated corrected radiation temperature. The FWHM, $\Delta V$, and the central velocity, $V_{peak}$, for which the maximum corrected radiation temperature value, $T_{peak}$, occurred are calculated by fitting Gaussian lines to the spectra. The coordinates of the center of NGC 5471 are $\alpha = 14^h02^m43.5^s$ and $\delta = 54^\circ38'09''0$. 

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ruary and April and 1997 February and April. This millimeter array has six antennae, which have diameters of 10.4 m. Two configurations of the array (A and C) were combined so that the synthesized beam is 2\'62 × 2\'03 for NGC 5461 and 3\'14 × 2\'73 for NGC 5462. The total track length was 16 hr for each region in each configuration. Typical single-sideband system temperatures at the zenith were 600–1000 K. All four independent correlator modules of the digital spectrometer system were used to observe the $^{12}$CO $J = 1 \rightarrow 0$ line with an effective bandwidth of 126 MHz (328 km s$^{-1}$) and a resolution of 1 MHz (2.6 km s$^{-1}$).

To reduce the data from the OVRO interferometer, we used the mma software package, which is written and maintained by the Caltech millimeter interferometry group (Scoville et al. 1993). For the two tracks of NGC 5461, Neptune and the quasar 3C 273 were used for the flux calibration measurements, which agreed to within 20%. For the two tracks of NGC 5462, one was calibrated with Uranus observations, and the other with the quasar 3C 345. The flux measurements from these two tracks agreed to within 10%.

The gain calibrator was the quasar 1418+546 [$\alpha (1950) = 14^h18^m06^s.2$ and $\delta (1950) = +54^\circ36'57''8$], which is unfortunately fairly weak. The average measured flux during the NGC 5461 observations was 0.80 Jy, while the flux during the NGC 5462 observations 1 yr later was 0.55
Jy. Since it is possible that the intrinsic brightness of the gain calibrator changed during the course of a year, we adopt these two separate values for the remaining analysis.

The data sets were edited to remove poor data, with the main criterion being that the coherence on the gain calibrator was higher than 50%. We determined passband calibration for the NGC 5461 tracks using the quasars 3C 273 and 3C 454.3. For the NGC 5462 tracks, the quasars 3C 454.3 and 3C 345 were used for passband calibration.

After the basic reduction was completed, we used Miriad (Sault, Teuben, & Wright 1995) to map and clean the data. Because the S/N was relatively small, we used natural weighting. All channel maps were cleaned to the 1.5 \( \sigma \) level with fewer than 1000 iterations. The rms noise and the maximum signal for the maps integrated over 52 km s\(^{-1}\) were 0.025 and 0.12 Jy beam\(^{-1}\) for NGC 5461, and 0.022 and 0.09 Jy beam\(^{-1}\) for NGC 5462. The rms noise and the maximum signal for the 1 MHz channel maps were 0.10 and 0.36 Jy beam\(^{-1}\) for NGC 5461, and 0.10 and 0.33 Jy beam\(^{-1}\) for NGC 5462.

Once the cleaning process was completed, we identified candidate GMCs in the maps. Three different types of plots were used. The integrated map is a plot that has been integrated over a wide velocity range (52 km s\(^{-1}\)) to include all of the emission. The channel maps are a series of maps where the region is plotted by integrating over one channel only (2.6 km s\(^{-1}\)). Finally, the optimum map for each cloud is integrated only over the velocity range in which a given feature is visible at the 3 \( \sigma \) level or better.

It must be stated in no uncertain terms that the process of identifying GMCs is fairly subjective. We have chosen three relatively conservative criteria so that the results inspire some confidence. The first criterion used to identify the GMCs is that the feature should be at least 2 \( \sigma \) in the integrated map. The second criterion required features to persist at the 3 \( \sigma \) level over two consecutive channels; this method, however, could result in underestimating the number of clouds, especially the ones with a narrow velocity width. The best velocity range for each GMC candidate was determined from the channel maps, and for each feature the optimum map integrated for the appropriate velocity range was generated. The third criterion required the feature to have signal of at least 3 \( \sigma \) in the optimum map. It is possible for the second criterion to be satisfied, but not the third if the features drift slightly from channel-to-channel so that the "optimum" integrated flux is less than 3 \( \sigma \) above the noise.

The integrated map of NGC 5461 (Fig. 3) has 33 features with peak fluxes of at least 2 \( \sigma \). Of the 33 features that appear in the integrated map, nine can be seen at the 3 \( \sigma \) level in two consecutive channels of the channel maps. In addition, we have also considered two other features (4 and 6 in Fig. 3) that appear on the integrated map and in three consecutive channels at the 2 \( \sigma \) level. Of the 11 GMC candidates, one is eliminated by the third criterion, i.e., the total flux in the optimum map is not 3 times higher than the noise of the optimum map. The rms noise determined in the optimum maps varies between 0.05 and 0.069 Jy beam\(^{-1}\) depending on the number of channels over which the signal has been integrated.
The characteristics of the 10 GMCs are given in Table 4. The positions were determined from the optimum maps. The sizes are not deconvolved from the synthesized beam; no cloud appears significantly larger than the beam in both dimensions, and thus we can place only upper limits on the true size of the clouds. The cloud positions are given for the center of the peak of the GMC in terms of offsets from the field center with an estimated uncertainty of 0.5. Two features, clouds 7 and 10, have similar coordinates, but they are separated in velocity space. Table 4 also includes the integrated flux measured from the optimum map. We calculated the equivalent brightness temperature, $T_B$, by multiplying the peak flux in a one-channel map by the conversion factor from janskys to kelvins (17.3 K Jy$^{-1}$). These brightness temperatures (4.5–8.1 K) are larger than those found in the GMCs toward M33 (Wilson & Scoville 1990) despite the fact that the GMCs in M33 are resolved and much closer. These large brightness temperatures suggest that the GMCs in M101 are close to being resolved.

The emission from NGC 5462 is much weaker than that from NGC 5461; in fact, the emission is so much weaker that there are no features that appear in consecutive channels at the 3σ level. If all the positive features are added, then the upper limit to the total flux from the region is less than 16 Jy km s$^{-1}$.

3. MOLECULAR MASS FROM THE EMPIRICAL METHOD

3.1. Mass of Individual GMCs in NGC 5461

The column density can be calculated via an empirical relation based on data that suggest that the column density of hydrogen, $N_{H_2}$, is linearly proportional to the observed radiation temperature integrated over the emission line of $^{12}$CO $J = 1 \rightarrow 0$ (Scoville & Sanders 1987; Digel et al. 1997). The constant of proportionality, $X$, is defined by (Bronfman et al. 1988)

$$X = \frac{N_{H_2}}{T_B \Delta v}.$$  

(1)

The range of $X_{\text{Gal}}$ found in the literature is $(1–12) \times 10^{20}$ cm$^{-2}$ (K km s$^{-1}$)$^{-1}$ (Digel et al. 1997), and we assume a value of $X_{\text{Gal}} = 3 \times 10^{20}$ cm$^{-2}$ (K km s$^{-1}$)$^{-1}$. However, the $X$ factor probably depends on the metallicity of the gas. It has been suggested that galaxies with lower metallicity than that of the Milky Way have higher values of $X$ (Wilson 1995) with

$$\log (X/X_{\text{Gal}}) = (5.95 \pm 0.86) - (0.67 \pm 0.10)[12 + \log (O/H)].$$  

(2)

The giant H II regions of M101 have low metallicities, so the value of $X$ should be adjusted: the value of $12 + \log (O/H)$ for NGC 5461 is 8.39 ± 0.08, while for NGC 5471 it is 8.05 ± 0.05 (Torres-Peimbert, Peimbert, & Fierro 1989).

The uncertainties introduced by the value of $X$ may be severe, especially in a galaxy with intense star formation (Maloney & Black 1988). However, the use of the $X$ factor is a standard way to estimate molecular cloud masses, so we adopt an initial value of $X$ correcting for the known metallicity of these regions and compute the resulting molecular gas mass with another, usually more reliable, virial mass to determine an appropriate value of $X$ for the H II regions in M101. As a starting point, we use the value of $X_{\text{NGC 5461}} = 6 \times 10^{20}$ cm$^{-2}$ (K km s$^{-1}$)$^{-1}$ for NGC 5461. The hydrogen column density can be obtained from equation (1), and the molecular mass in terms of flux density, $S_\nu$, can be written as (Wilson & Scoville 1990)

$$M_{\text{mol}} = 1.61 \times 10^4 M_\odot \left(\frac{X}{3 \times 10^{20} \text{ cm}^{-2} \text{ (K km s}^{-1})^{-1}}\right) \left(\frac{d}{\text{Mpc}}\right)^2 \left(\frac{S_\nu}{\text{Jy km s}^{-1}}\right).$$  

(3)

We use equation (3) to calculate the masses of the individual GMCs (Table 5); we have corrected the fluxes (and masses) for the primary beam fall-off. With this equation, the individual features in NGC 5461 have masses of $(2–9) \times 10^6 M_\odot$ and appear to be much more massive than the GMCs in the Milky Way, which have masses typically around $10^5 M_\odot$.

As a check on these masses, we compare the molecular masses to the virial masses (Johansson et al. 1998). If the virial mass is less than or equal to the molecular mass, then the clouds are considered gravitationally bound. The virial mass is adapted (by converting $\sigma_{1D}$ to $\Delta V_{\text{FWHM}}$) from Rand (1993):

$$M_{\text{vir}} = 95 M_\odot \left(\frac{\Delta V_{\text{FWHM}}}{\text{km s}^{-1}}\right)^2 \left(\frac{D}{\text{pc}}\right).$$  

(4)

We define the diameter, $D$, to be $1.4D_{\text{FWHM}}$ to include all the emission from the GMC and for consistency with previous

| Cloud | Central Velocity (km s$^{-1}$) | Dimensions (pc x pc) | Offset Position (arcsec, arcsec) | $\Delta v$ (km s$^{-1}$) | Total Integrated Flux (Jy km s$^{-1}$) | $T_B$ (K) |
|-------|-------------------------------|----------------------|---------------------------------|--------------------------|---------------------------------------|-----------|
| 1     | 263                           | 99 x 90              | (19, 20)                        | 7.8                      | 2.6 ± 0.9                             | 7.5       |
| 2     | 270                           | 108 x 90             | (–2, –2)                        | 10.4                     | 4.4 ± 1.0                             | 5.3       |
| 3     | 270                           | 180 x 81             | (0, –7)                         | 5.2                      | 1.9 ± 0.5                             | 5.5       |
| 4     | 271                           | 99 x 73              | (–21, –19)                      | 7.8                      | 3.0 ± 0.9                             | 8.1       |
| 5     | 274                           | 94 x 73              | (–6, –2)                        | 7.8                      | 1.2 ± 0.3                             | 4.5       |
| 6     | 276                           | 140 x 90             | (–15, –13)                      | 7.8                      | 4.7 ± 1.2                             | 6.1       |
| 7     | 282                           | 126 x 81             | (10, 15)                        | 7.8                      | 3.3 ± 0.7                             | 6.6       |
| 8     | 285                           | 99 x 73              | (17, 28)                        | 5.2                      | 2.1 ± 0.6                             | 7.7       |
| 9     | 285                           | 108 x 90             | (–9, –25)                       | 5.2                      | 2.2 ± 0.6                             | 6.0       |
| 10    | 298                           | 180 x 90             | (11, 15)                        | 5.2                      | 2.8 ± 0.9                             | 5.7       |

Note.—The dimensions are not deconvolved from the beam. The offset positions are with respect to the center of NGC 5461: $x = 14^\circ01' + 55''$ and $\delta = 54^\circ33'31''$. The integrated fluxes and brightness temperatures have been corrected for the primary beam fall-off in sensitivity.
studies (Wilson & Scoville 1990). In our calculations, we have assumed an upper limit for $D_{\text{FWHM}}$ of 80 pc because none of the GMCs are resolved from the beam in both dimensions; therefore, the virial masses estimated are upper limits based on a diameter of 110 pc. These masses have been tabulated in Table 5 along with the masses found by the empirical method and the expected diameter, $D_{\text{exp}}$, given the observed velocity dispersion, $\Delta V_{\text{obs}}$, and the size:line width relation (Sanders, Scoville, & Solomon 1985; McLaughlin & Pudritz 1996):

$$\frac{\Delta V}{\text{km s}^{-1}} = 1.2 \left(\frac{D}{\text{pc}}\right)^{0.5}.$$  

(5)

We find that the virial mass of each cloud is generally an order of magnitude smaller than the molecular mass calculated from the metallicity-corrected $X$ factor and is similar to the masses of the GMCs in the Milky Way. We have more confidence in the universality of the virial theorem, and thus this large discrepancy suggests that a smaller value of $X$ for the giant H II regions in M101 is more appropriate. The physical justification for adopting a different value of $X$ is that $X$ depends on temperature, and the observed high brightness temperature indicates that the gas is hot. If these clouds obey the Galactic size:line width relation, they have rather low filling factors within the OVRO beam, and their true brightness temperatures would be even higher than what is observed. It is possible that the high temperature of the gas lowers the value of $X$ in a star-forming region (Maloney & Black 1988). The average value of the ratio $M_{\text{mol}}/M_{\text{vir}}$ for the GMCs in NGC 5461 is $10 \pm 4$, which suggests that the appropriate value of $X_{\text{NGC 5461}}$ is $6 \times 10^{19}$ cm$^{-2}$ (K km s$^{-1}$)$^{-1}$, or approximately 5 times smaller than the canonical Galactic value (and 10 times smaller than the metallicity-corrected value). We adopt the virial mass as the most correct estimate of the mass of the GMCs. These observations are the first to demonstrate a clear decrease in the value of $X$ because of heating by intense star formation. We adopt the same value for $X_{\text{NGC 5462}}$ because the two giant H II regions have similar metallicities. For NGC 5471, we use the value $X_{\text{NGC 5471}}$ of $12 \times 10^{19}$ cm$^{-2}$ (K km s$^{-1}$)$^{-1}$ because of its lower metallicity.

3.2. Mass of the Associations of GMCs

After examining the masses of the individual GMCs, we use equation (3) to calculate the mass of the entire association of GMCs for each region using the appropriate value of $X$. With observations from the NRAO 12 m telescope (Table 3), we obtain the integrated intensity by multiplying the integrated $T_R^*$ with the factor 34 Jy K$^{-1}$. From the integrated intensity, we calculate the total molecular mass from equation (3) (Table 6).

The integrated flux from the OVRO map was measured from the integrated map over a velocity range of 52 km s$^{-1}$ of $^{12}$CO $J = 1 \rightarrow 0$ emission. The value for the integrated flux density is $33 \pm 13$ Jy km s$^{-1}$, which corresponds to $(60 \pm 23) \times 10^5 M_\odot$. This result from the OVRO millimeter array is smaller than the mass obtained from the single-dish data (12 m telescope). To explain the difference, one might evoke the presence of a constant, broadly distributed contribution to the intensity, which would have been undetected by the interferometer (Wilson & Scoville 1990). The same explanation might be appropriate for the measurements of NGC 5462 (Table 6).

### Table 5

| Molecular Cloud | $\Delta V_{\text{obs}}$ (km s$^{-1}$) | $D_{\text{exp}}$ (pc) | $M_{\text{vir}}$ ($10^3 M_\odot$) | $M_{\text{mol}}$ ($10^3 M_\odot$) | Corrected $M_{\text{mol}}$ ($10^3 M_\odot$) |
|-----------------|---------------------------|-----------------|------------------|------------------|-------------------|
| 1               | 7.8                       | 42              | $<6 \pm 2$       | 46 $\pm 16$      | 5 $\pm 2$         |
| 2               | 10.4                      | 75              | $<11 \pm 3$      | 78 $\pm 17$      | 8 $\pm 2$         |
| 3               | 5.2                       | 19              | $<3 \pm 1$       | 34 $\pm 9$       | 3 $\pm 1$         |
| 4               | 7.8                       | 42              | $<6 \pm 2$       | 54 $\pm 16$      | 5 $\pm 2$         |
| 5               | 7.8                       | 42              | $<6 \pm 2$       | 22 $\pm 5$       | 2 $\pm 1$         |
| 6               | 7.8                       | 42              | $<6 \pm 2$       | 85 $\pm 22$      | 8 $\pm 2$         |
| 7               | 7.8                       | 42              | $<6 \pm 2$       | 59 $\pm 13$      | 6 $\pm 1$         |
| 8               | 5.2                       | 19              | $<3 \pm 1$       | 38 $\pm 11$      | 4 $\pm 1$         |
| 9               | 5.2                       | 19              | $<3 \pm 1$       | 40 $\pm 11$      | 4 $\pm 1$         |
| 10              | 5.2                       | 19              | $<3 \pm 1$       | 50 $\pm 16$      | 5 $\pm 2$         |

**Note.**—The velocity dispersion, $\Delta V_{\text{obs}}$, of the 10 clouds in NGC 5461 is presented along with the expected size, $D_{\text{exp}}$, given the M33 size:line width relationship. In addition, we present the virial masses and the empirical masses of the GMCs in NGC 5461. The uncertainties in the empirical masses take into account only the uncertainty in the measurement of the integrated flux. The corrected empirical masses are calculated for the new reduced value of $X$ toward NGC 5461.

### Table 6

**Summary of Masses Obtained in the Analysis**

| Region | Mass ($\times 10^5 M_\odot$) |
|--------|----------------------------|
| NGC 5461: |
| LTE* | 400 (350–500) |
| Empirical (NRAO 12 m) | 150 $\pm 30$ |
| Empirical (OVRO) | 60 $\pm 23$ |
| Average cloud in NGC 5461: |
| Empirical (OVRO) | 5 |
| NGC 5462: |
| LTE* | $>35$ |
| Empirical (NRAO 12 m) | 22 $\pm 7$ |
| Empirical (OVRO) | $<30$ |
| NGC 5471: |
| Empirical (NRAO 12 m) | $<65 \pm 24$ |

* Method depends on the value of the coupling efficiency, $\eta_c$. 

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**Table 5:** Sizes and Masses of GMCs in NGC 5461

**Table 6:** Summary of Masses Obtained in the Analysis
The mass of molecular gas associated with NGC 5461 is greater than the masses associated with the other two H II regions. Although the calculations indicate that NGC 5462 has a slightly smaller molecular mass than NGC 5471, their allowed values are the same to within their uncertainties. The uncertainties in the total molecular mass are derived from the uncertainty in the integrated radiation temperature; the (potentially more significant) systematic uncertainty in the value of $X$ has been ignored.

4. LTE ANALYSIS

In this section, we calculate the optical depth and the column density based on the assumption that the gas is in LTE. For the LTE analysis, we used $^{12}$CO and $^{13}$CO J = 2 → 1 data obtained at the JCMT. The LTE method is frequently used to calculate the physical properties of molecular gas, especially when isotopomers of CO or of other molecules such as CS and NH$_2$ have been observed (e.g., Lada & Fich 1996; Giannakopoulou et al. 1997). The $^{12}$CO J = 2 → 1 and $^{13}$CO J = 2 → 1 transitions have very similar frequencies, so the ratio of the transparency of the gas in the two transitions is approximately given by

$$\frac{1 - e^{-12\tau_i}}{1 - e^{-13\tau_i}} = \frac{k^{12} T_R/\nu_{12} - e^{-h\nu_{12}/kT_{bg}}}{k^{13} T_R/\nu_{13} - e^{-h\nu_{13}/kT_{bg}}},$$

where $\nu$ is the frequency of the transition, $\tau_i$ is the optical depth, $T_R$ denotes radiation temperature, and $T_{bg} = 2.73$ K is the temperature of the microwave background.

We can calculate $^{13}$r, if we assume a value for the abundance ratio $\psi = (^{12}$CO)/(^{13}$CO). This ratio may increase with the galactocentric distance (Langer & Penzias 1990): $\psi$ has been measured to be as low as 24 within 4 kpc and as high as 79 at 12 kpc from the center of our Galaxy. For the distance of the two giant H II regions from the center of M101 (between 4 and 6 kpc), we expect the most appropriate ratio to be at the lower end of these values.

Since we have assumed that the gas is in LTE, the kinetic temperature $T_k$ is equal to the excitation temperature and is given by

$$T_k = \frac{h\nu/k}{\ln \{1 - e^{-\nu}[kT_R/\nu - (e^{h\nu/kT_{bg}} - 1)^{-1} - 1]\}},$$

The Appendix contains a detailed discussion of how we obtained the radiation temperature. The values of the kinetic temperature are between 8 and 25 K, which are fairly low for a star-forming region. Even lower values of 4–6 K are found for NGC 5462. However, these are average temperatures over large volumes of gas. Near young stars, the temperature of the gas will likely be much higher. The smaller value of $X$ found for the GMCs in NGC 5461 is possible evidence of higher temperatures, as are the large brightness temperatures of 4–8 K observed in the $^{12}$CO J = 1 → 0 line.

From references such as Mitchell et al. (1995) and Giannakopoulou et al. (1997), we find that the total integrated $^{13}$CO column density, $N_{^{13}$CO}, is given by

$$N_{^{13}$CO} = \frac{3k}{8B_r \pi^2 \mu^2} \int e^{h\nu/\mu k} \frac{T_k}{l(l+1)} \left(\frac{T_k + hB_r/3k}{1 - e^{-h\nu/kT_k}}\right)^{13} \tau_e \, dv,$$

where the rotational moment of CO is $B_r = 5.764 \times 10^{10}$ Hz and the electric dipole moment of CO is $\mu = 1.12 \times 10^{-19}$ esu cm (Chantry 1979). For the error analysis of the column density, we use a robust bootstrap method (Efron & Tibshirani 1993). We estimated the probability distribution of the column density, via equation (8), by a Monte Carlo method in which Gaussian random numbers representing $^{11}$T$_R$ and $^{13}$T$_R$ are generated with population means equal to the measured temperatures and with population standard deviations equal to the measured uncertainties in the temperature. From the characteristics of these distributions, one can obtain the uncertainty in the amount associated with the total column density.

To obtain the column density $N_{^{13}$CO} for each region, we summed the column densities per channel over all channels. For a channel to be included, we required that its peak $^{13}$CO signal is at least 3 $\sigma$, and its peak $^{13}$CO signal is at least 2 $\sigma$. The median column density for NGC 5461 is $6.5 \times 10^{15}$ cm$^{-2}$. These criteria result in a lower limit of $1.2 \times 10^{15}$ cm$^{-2}$ for the value of the column density (and consequently of the mass) of NGC 5462, which only has one channel that meets the restrictions.

The column density is used to obtain the total molecular mass for the three regions. Since the main constituent of the interstellar medium is molecular hydrogen, the $^{13}$CO column density obtained above needs to be extrapolated to that of $^{12}$CO, $N_{^{12}$CO}, which in turn will be converted to the H$_2$ column density, $N_{H_2}$. The values of the isotopomer ratio, $\psi$, and of the ratio of the column density of molecular hydrogen to the column density of CO are uncertain. We adopt a value of $\psi = 20$ because the giant H II regions are fairly near the center of M101 (also § 5). In addition, we need to determine a suitable value for the proportionality constant ($N_{H_2}/N_{^{13}$CO}$). The canonical value of this parameter is $10^4$ for the Galaxy (Snell 1981). However, this ratio depends on metallicity. Since NGC 5461 and NGC 5462 are 4 times more metal-poor and NGC 5471 is 9 times more metal-poor than the Milky Way (Torres-Peimbert et al. 1989), we adopt values of $4 \times 10^4$ and $10^5$, respectively, for these H II regions.

The mass of the H$_2$ gas is found by multiplying the total H$_2$ column density, $N_{H_2}$, by the beam area, $A$, and the mass of a hydrogen molecule $m_{H_2}$. Finally, the fractional helium abundance (10% by number) is taken into account in order to obtain the total mass within a beam. Thus the total molecular gas mass for NGC 5461 and NGC 5462 is

$$M_{mol} = 6.3 \times 10^{-9} M_\odot \left(\frac{N_{^{13}$CO}}{cm^{-2}}\right) \left(\frac{A}{pc^2}\right).$$

The masses of the molecular gas are given in Table 6. These masses are much larger than Galactic GMCs, which have typical values of $10^5$ $M_\odot$ (Blitz 1993). Large masses are expected from regions as big as those observed (700 pc or 20°), which would contain an association of GMCs.

5. LVG ANALYSIS

There are two extreme non-LTE approaches in dealing with the radiative transfer problem. One approach is to assume that there is no global motion: all the emission is a result of small-scale thermal motions and turbulence. The second approach is to assume that the gas cloud has an LVG, which means that the CO emission from one part of the cloud will be Doppler-shifted to a frequency that will
not be reabsorbed by gas in other parts of the cloud (Scoville & Solomon 1974). Under these conditions, the emission from a molecule will be absorbed only by neighboring molecules, and the radiative transfer can be solved locally (Goldreich & Kwan 1974). The first approach is called the microturbulence method, and the second approach is called the LVG method. The two non-LTE approaches typically produce results that agree within the errors of the methods, which are a factor of 3 because of uncertainties in geometry (White 1977). We have used just one non-LTE method, the LVG method, to compare with our LTE analysis (White 1977; Hasegawa, Rogers, & Hayashi 1991).

To estimate the physical conditions in the GMCs of M101, we have used the LVG code written by J. Arlett and L. Avery for a spherical, uniform cloud. This program computes the radiation temperatures of various CO transitions for ranges of kinetic temperature, density of H$_2$, and an abundance parameter, which is defined as $(N_{CO}/N_{H_2})/(dV/dr)$. These radiation temperatures were fitted to the observed values (Table 7) by minimizing a chi-squared statistic to give the best fit for kinetic temperature, density, and abundance. In addition to these parameters, the LVG results depend on the isotopomer ratio, $\psi = (^{12}$CO)/($^{13}$CO). We found that the best fits occur for $\psi = 20$, which is in agreement with the observed value in the Milky Way (Langer & Penzias 1990).

For NGC 5461, we found reasonable fits both for low temperatures ($T_K = 30–90$ K) and for high temperatures ($T_K = 230–250$ K); the best fit was for $T_K = 60$ K. However, the best fit for density, $n_H = 3 \times 10^3$ cm$^{-3}$, was the same for both ranges of temperature. A GMC with a diameter of 112 pc and this density has a mass of $1.3 \times 10^8 M_\odot$, which is 2 orders of magnitude larger than those obtained with the empirical method (Table 6). The clouds are not resolved, and we do not expect the cloud to be completely uniform: the volume-averaged density is usually substantially smaller than $10^3$ cm$^{-3}$ (Wilson & Scoville 1990). By comparing the results from the LVG analysis and the empirical method, we conclude that the filling factor is on the order of 1% for the clumpy material. This low filling factor indicates that the gas emitting the CO has formed dense clumps, which are surrounded by a lower density envelope. A similar situation is observed in the molecular gas of 30 Dor (Johansson et al. 1998): the intense radiation field is considered the reason for the dissociation or ionization of the gas in the envelope.

The LVG analysis cannot be done for NGC 5462 because there are only two available ratios (Table 7). The LVG analysis is not conclusive with only two ratios (Thornley & Wilson 1994), but one can use the available ratios to make some general statements about the physical properties of the gas. Because the $^{12}$CO $(J = 3 \rightarrow 2)/(J = 2 \rightarrow 1)$ ratio for NGC 5462 is larger than that of NGC 5461, the molecular gas in NGC 5462 may be warmer than the molecular gas around NGC 5461. One expects from the Boltzmann equation that for usual temperatures of quiescent molecular gas (10 K) the second level is more populated than the third level, which means that for cold gas the ratio $^{12}$CO $(J = 3 \rightarrow 2)/(J = 2 \rightarrow 1)$ is less than unity; however, in the case of NGC 5462, the ratio is larger than unity, which implies that the gas is probably considerably hotter than typical quiescent gas.

6. MASSES AND TEMPERATURES

NGC 5461 is the brightest H II region in CO emission; therefore, the data set for NGC 5461 is the most complete of all the giant H II regions in M101. There are two estimates (from the LTE and from the empirical estimate using the NRAO data) for the mass of the association of GMCs in NGC 5461, which range in value from $(15–40) \times 10^6 M_\odot$. Although the discrepancy of a factor of 3 is not surprising when we consider the uncertainties in the methods involved, the difference could be partially due to an underestimate of $\eta$, (see the Appendix). It is likely that there are GMCs in NGC 5461 that were not detected and would have contributed in increasing the coupling efficiency.

Both the LTE method and the empirical method suggest that NGC 5462 has roughly an order of magnitude less molecular mass than NGC 5461. This conclusion is consistent with the fact that the molecular gas in NGC 5462 was not detected with the OVRO array. NGC 5462 might not be as massive as NGC 5461, but it may be hotter than NGC 5461 since the $^{12}$CO $(J = 3 \rightarrow 2)/(J = 2 \rightarrow 1)$ ratio in NGC 5462 is even higher than the extraordinary cloud NGC 604-2 in M33. Unfortunately, the uncertainty of this ratio for NGC 5462 is fairly high; within its uncertainty, it agrees with normal clouds in M33 and IC 10 (Petitpas & Wilson 1998).

NGC 5471 is significantly weaker in CO emission than NGC 5462 and NGC 5461, so the only observations that were made of NGC 5471 were in $^{12}$CO $J = 1 \rightarrow 0$ and $J = 2 \rightarrow 1$ emission. Unlike NGC 5462, NGC 5471 is several kpc away from the center of M101 and, therefore, has considerably lower metallicity than regions closer to the center of M101. With the higher adopted value for $X$ for this region, the upper limit to the molecular mass in NGC 5471 is comparable to that of NGC 5462. If the $X$ factor is, in fact, even larger, then the mass of the molecular gas in NGC 5471 could even be comparable to that of NGC 5461. However, a more probable explanation for the deficiency of CO emission in NGC 5471 is that there is genuinely less molecular gas present. A clue to this problem is the presence of large amounts of atomic gas near the giant H II region (Kamphuis 1993). Perhaps the atomic gas was converted to molecular gas more slowly in NGC 5471 than in the other two giant H II regions, or perhaps more of the molecular gas has been rapidly dissociated to atomic gas. There is more discussion on this topic in § 7.

One possible result of star formation is that the molecular gas becomes hotter. One of the diagnostics of high temperatures is the $^{12}$CO $(J = 3 \rightarrow 2)/(J = 2 \rightarrow 1)$ ratio. NGC 5461 has a similar $^{12}$CO $(J = 3 \rightarrow 2)/(J = 2 \rightarrow 1)$ ratio to the clouds in M33 that are associated with H II regions (Wilson, Walker, & Thornley 1997). However, the ratio for NGC 5461 does not approach the value for the GMC NGC 604-2,
which is, indeed, very high compared to other ratios seen in M33 and other galaxies. An explanation for the lower value of the $^{12}$CO ($J = 3 \rightarrow 2)/(J = 2 \rightarrow 1)$ ratio in NGC 5461 compared to that found in other giant H II regions is that the clouds in NGC 5461 may have a mixture of warm and hot gas. The dominant warm component could be similar in temperature and density to the GMCs in M33 associated with H II regions (Wilson et al. 1997).

7. STAR FORMATION

The main motivation of this paper is to understand the connection between the molecular gas in M101 and the existence of the bright stars that produce the giant H II regions. In the Milky Way, the masses of GMCs that are affiliated with OB associations are $(1-7) \times 10^5 M_\odot$ (Williams & McKee 1997). From this observational result, Williams & McKee (1997) suggest that the probability a GMC will contain a very bright massive star (O9.5) increases as the mass of the cloud increases. However, the GMCs in NGC 5461 have masses that are much smaller than those required to form many bright O stars, according to Figure 7 of Williams & McKee (1997). Perhaps the star-forming efficiency, and not the mass of the clouds, is the key issue for regions with intense star formation.

Intense star formation influences and is influenced by the surrounding ambient ionized and atomic gas. It is instructive to consider the correlation of molecular gas with ionized and atomic gas. One might expect that molecular and ionized hydrogen, which is observed via the Hα transition, should be associated with each other. In Figure 4, the CO peaks are compared with a recent Hα map that was kindly provided by R. C. Kennicutt. The CO clouds are denoted by stars to distinguish them from the contours of the Hα map.

The CO peaks are typically displaced from the peak of the Hα image by 2°–5° or, at the distance of M101, 70–180 pc. A possible reason, which was used to explain the same type of anticorrelation in M51 (Rand 1993), is that the presence of gas with high surface density increases the extinction from the associated dust. The radiation from the ionized gas is obstructed, and therefore the Hα emission is anticorrelated with the molecular gas.

Figure 5 presents the CO clouds in NGC 5461 superimposed on a high-resolution (9') H I contour map kindly provided by R. Braun. The GMCs are denoted with stars. The CO peaks are displaced compared to the peak of the H I image by 3°–10° or, at the distance of M101, 100–360 pc. A possible explanation for this displacement is that the radiation from the young massive stars in the H II regions may have dissociated the molecular gas to atomic gas; this explanation was used for M51 where a similar displacement was observed (Vogel, Kulkarni, & Scoville 1988). Unfortunately, the uncertainty of the positions of the H I map, 4", is fairly high; it is possible that the observed offset is not significant.

A large-scale study of the atomic gas in M101 was conducted with 6' resolution (Braun 1995). Two of the several positions observed coincide with the giant H II regions NGC 5461 and NGC 5471. The atomic masses for the two regions are $5 \times 10^7$ and $4 \times 10^7 M_\odot$, respectively, which are a few times higher than the corresponding molecular mass observed in similar beams. This result is consistent with the observed ratios of atomic to molecular gas in a sample of 27 Sc galaxies (Young & Scoville 1991).

Despite the fact that the masses of the atomic gas for NGC 5461 and NGC 5471 are similar, their empirical molecular masses are different by a factor of 3. Why does NGC 5461 have so much more molecular gas than NGC 5471? One possibility is that NGC 5461 has a more efficient mechanism to convert atomic to molecular gas than NGC...
function. The ßux at 60 \mu m for NGC 5461 is 9.65 Jy, and for NGC 5471 it is 1.81 Jy (NGC 5462 is not detected as a point source). For the calculation, it has been assumed that \rho = 3 \text{ g cm}^{-2}, Q_{em}/a = 340 \text{ cm}^{-1}, and T = 30 \text{ K} (Fich & Hodge 1991), which are canonical values. With these assumptions, the dust mass for NGC 5461 is \(5 \times 10^6 M_\odot\), while for NGC 5471 the dust mass is \(9 \times 10^4 M_\odot\). If the gas-to-dust ratio is assumed to be a typical value of 600 for Sc galaxies (Young & Scoville 1991, and references therein), then the total gas mass in NGC 5461 is \(3 \times 10^8 M_\odot\), and the total gas mass in NGC 5471 is \(5 \times 10^7 M_\odot\), which is in agreement with the sum of all gas components in these regions (Table 8).

The star formation efficiency is the ratio of the mass of stars formed in the region to the sum of the stellar and molecular masses of the region (Lada 1992). Recently, the mass of stars (\(M > 2 M_\odot\)) in a small portion of NGC 5461 has been estimated from UV ßuxes (Rosa & Benvenuti 1994); however, to compare this result with our data we must scale the mass of stars to include all stars down to 0.1 \(M_\odot\), and we must scale the ßux to correct for the small aperture used (1\arcsec). We estimate from Table 9 in Miller & Scalo (1979) that the ßrst scale factor is 2.6 and from Figure 1 in Rosa & Benvenuti (1994) that the second scale factor is 4 for both NGC 5461 and NGC 5471. The masses of the stars and the star formation efßciencies in NGC 5461 and NGC 5471 calculated in this manner are given in Table 8. The star-forming efßciencies are slightly larger than the efßciencies of a few percent (1\%–4\%) observed in several clouds in the Milky Way such as the Taurus-Auriga, Orion A, and Orion B clouds (Evans & Lada 1991). Thus the GMCs in these giant H II regions are somewhat more efßcient in creating stars than molecular clouds in our Galaxy. Perhaps the mass of the atomic gas should be included in the calculation of the star efßciency if the molecular gas has already been dissociated to H_\text{I}. However, the H_\text{I} has been found at great distances from the molecular cloud, especially in the case of NGC 5471. It is not obvious that the H_\text{I} is directly connected with the star-forming regions.

8. CONCLUSIONS

In this paper, the molecular components of three giant H II regions in the spiral galaxy M101 have been investigated with new observations from two single-dish telescopes (JCMT and NRAO 12 m) and from the OVRO millimeter array.

1. NGC 5461 is the only H II region with strong enough emission to be detected with the OVRO millimeter array. The mass of the GMCs in NGC 5461 was calculated empirically and from the virial theorem, and we found that the appropriate X factor toward the giant H II regions is 5 times smaller than \(X_{Gal}\). These data provide the ßrst empirical demonstration that the value of X may decrease in regions with intense star formation. The corrected empirical masses of the large GMCs cover a range of \((2–8) \times 10^5 M_\odot\), which is comparable to that observed in the Galaxy. Using this determined value of X, we calculate the mass of the associations of GMCs in NGC 5461, NGC 5462, and NGC 5471.

2. The molecular mass for the association of GMCs in NGC 5461 is calculated to be \((15–40) \times 10^6 M_\odot\). The higher value in the range comes from the empirical method using NRAO data of NGC 5461. The discrepancy would be resolved if the \(\eta_c\) was larger. This efßciency probably is larger because there could be more GMCs in NGC 5461 that were not detected. The interferometric data provide a lower mass \((6 \times 10^6 M_\odot)\) because the ßux from extended low-level emission is typically lost in an interferometer. The molecular mass toward NGC 5462 is estimated to be \((2.2–3.5) \times 10^6 M_\odot\). CO emission was not detected toward NGC 5471; the upper limit to the mass is \(6.5 \times 10^6 M_\odot\).

3. The gas emitting the CO is very dense—so dense that it cannot ßll up more than 1\% of the volume without exceeding the GMC mass limits. It is possible that the intense radiation ßeld in the vicinity of a giant H II region partially dissociates or ionizes portions of the molecular gas, leaving small dense cores in large sparse envelopes.

4. The molecular mass of the NGC 5461 association of clouds is accompanied by 1–2 times as much atomic mass. The fairly large ratio of atomic to molecular gas can be attributed either to slow formation of GMCs from the original atomic clouds or to efficient dissociation of the GMCs

\begin{table}[h]
\centering
\caption{Masses and Star-forming Efficiencies}
\begin{tabular}{lcccl}
\hline
Name            & Ionized Mass & Stellar Mass & Molecular Mass & Star Formation Efficiencies \\
                & \((\times 10^6 M_\odot)\) & \((\times 10^6 M_\odot)\) & \((\times 10^6 M_\odot)\) & \%
\hline
NGC 5461 \ldots & 30          & 1            & 15             & 6 \\
NGC 5471 \ldots & 14          & 0.8          & <6.5           & >11 \\
\hline
\end{tabular}
\end{table}

Note: The mass of the ionized gas is from Israel et al. 1975, and the stellar mass is estimated from Rosa & Benvenuti 1994 after correcting to include low-mass stars (\(M > 0.1 M_\odot\)) and the proper aperture size.
to atomic gas. An even stronger presence of atomic hydrogen is observed in the vicinity of NGC 5471; in this region, the atomic mass is an order of magnitude larger than the molecular mass. Perhaps NGC 5471 has not converted much of its atomic gas to molecular gas yet, or the molecular gas has been dissociated to form atomic gas. For both NGC 5461 and NGC 5471, the total gas mass can be extrapolated from the mass of the dust estimated from IRAS data. The estimates of the total gas mass from the dust are consistent with the sum of the molecular, ionized, and atomic masses.

5. The relatively normal masses observed toward the clouds in NGC 5461 reinforce the hypothesis that giant H II regions in M101 are so much brighter than the H II regions in our Galaxy because of the different properties of the natal clouds in M101. In particular, this paper suggests that the high star formation efficiency of the gas, and not the large mass of the cloud, is the key to the formation of giant H II regions in M101.

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APPENDIX

CALCULATING THE RADIATION TEMPERATURE, $T_R$, FROM OBSERVED TEMPERATURES

To calculate the radiation temperature, one needs $\eta_s$, the efficiency with which the antenna diffraction pattern couples to the source (Kutner & Ulich 1981):

$$T_R = \frac{T_A^*}{\eta_c \eta_{fss}} = \frac{T_A^*}{\eta_c},$$  \hspace{1cm} (A1)

where $\eta_{fss}$ is the efficiency of forward scattering and spillover. The model used for the integration takes into account both the size (as determined from the high-resolution OVRO data of NGC 5461) and the position of each GMC with respect to the center of the JCMT beam. We found that the coupling efficiencies for NGC 5461 are $0.056 \pm 0.024$ and $0.037 \pm 0.016$ for the two transitions $^{12}$CO $J = 2 \rightarrow 1$ and $J = 3 \rightarrow 2$, respectively.

One has to assume that the coupling efficiency for the gas in NGC 5462 is similar to NGC 5461 because there were no interferometric detections of clouds in NGC 5462. This assumption is probably not too bad because the values for the molecular mass obtained with the LTE method are within a factor of 2 or 3 from the values obtained from the empirical method, which does not utilize the coupling efficiency (Table 6).

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