1. INTRODUCTION

It is of fundamental importance in astronomy to understand the evolution of galaxies. Since a major constituent of galaxies is stars, the formation of stars is a fundamental process in galactic evolution. The properties of stars characterize the basic contents of galaxies and their time evolution. We understand from studies of the Milky Way that giant molecular clouds (GMCs), whose mass ranges from $10^3$ to $10^5 M_\odot$, are the principal sites of star formation and that this perhaps holds true in other galaxies as well. We also recognize that the GMC properties (e.g., $L_{CO}$—line width relation, index of mass spectrum) are similar among five galaxies in the Local Group according to the spatially resolved studies (Blitz et al. 2007). This supports the idea that studies of GMCs will be useful in understanding the fundamentals of galactic evolution through the formation and evolution of GMCs and star formation therein.

Observational studies of GMCs have been most effectively made by the millimeter interstellar carbon monoxide emission line at 2.6 mm, which allows us to probe molecular gas whose density is greater than $\sim 100$ cm$^{-3}$. We note that the most abundant species, molecular hydrogen, does not have appropriate line emissions in the millimeter and submillimeter region due to its zero permanent electric dipole moment and large separation between…

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the lowest energy levels, which are not excited significantly in the typical physical conditions of molecular clouds.

Recent advances in submillimeter observations have allowed us to determine physical parameters of molecular clouds over much larger ranges than in the millimeter region by comparing line intensities between different transitions. These submillimeter studies were initiated by the Swedish-ESO Submillimetre Telescope (SEST) 15 m telescope in Chile followed by instruments in Mauna Kea, Hawaii, and in the Swiss Alps at an altitude range from 3700 to 4200 m, including the Caltech Submillimeter Observatory (CSO) 10 m, James Clerk Maxwell Telescope (JCMT) 15 m, and KOSMA 3 m telescopes, and the Antarctic Submillimeter Telescope and Remote Observatory (AST/RO) 1.6 m telescope in Antarctica. Subsequently, in the 2000s, the development of new instruments at an altitude of ~5000 m in Atacama in northern Chile resulted in a superior capability because of the high altitude and dry characteristics of the site. The instruments installed in Atacama include the Atacama Submillimeter Telescope Experiment (ASTE) 10 m, APEX 12 m, and NANTEN 2 4 m telescopes. All these instruments are beginning to take new molecular data with significantly better quality than before in terms of noise level, as well as angular resolution. It is also noteworthy that the current frequency coverage extends as high as the 800 GHz band and even the terahertz region.

Among nearby galaxies that we can observe at reasonably high spatial resolutions, the Large and Small Magellanic Clouds offer us a unique opportunity to achieve the highest resolutions due to their unrivaled closeness, 50–60 kpc. In particular, the Large Magellanic Cloud (LMC) is actively forming stars in clusters and is an ideal laboratory for us to study star formation, particularly massive star formation in star clusters. In the LMC, the metallicity is a factor of ~3 lower than in the solar neighborhood (Dufour et al. 1982; Dufour 1984; Rolleston et al. 2002). In addition, the visual extinctions are lower and the FUV field is stronger in the LMC than in the Milky Way (Israel et al. 1986), characterizing the initial conditions of star formation.

The first spatially resolved complete sample of GMCs in a single galaxy has been obtained toward the whole LMC with the NANTEN 4 m telescope in 2.6 mm CO emission at 40 pc resolution (Fuks et al. 1999, 2001, 2007; Mizuno et al. 2001). These studies revealed the three types of GMCs in terms of star formation activities; type I is starless, type II is with H II regions only, and type III is associated with active star formation indicated by huge H II regions and young star clusters, where the stars identified are only O stars due to the sensitivity limitation. It also revealed that the lifetime of a GMC is as short as ~10^7 years (Fukui et al. 1999, 2001, 2007; Mizuno et al. 2001). These previous studies naturally place the LMC as one of the prime targets for submillimeter studies to derive the physical parameters of GMCs.

Another aspect that deserves our attention is that very young, rich stellar clusters are forming in the LMC. These are so-called populous clusters, which are very rare in the Milky Way and resemble globular clusters formed in the primeval Milky Way. The open clusters forming in the Milky Way are small in the number of stars and loose in spatial distribution. Along with the low metallicity of the LMC, it is an interesting possibility to use molecular data to investigate the formation mechanism of super star clusters at the molecular cloud stage.

In the past, there have been some studies that used the higher transitions (J = 2–1, J = 3–2, J = 4–3, J = 7–6) of CO spectra of the molecular clouds in the LMC (e.g., Sorai et al. 2001; Johansson et al. 1998; Heikkilä et al. 1999; Bolatto et al. 2005; Israel et al. 2003; Kim et al. 2004; Kim 2006). These studies suggest that the molecular gas may be warmer and/or denser than in the Milky Way.

Johansson et al. (1998) used the SEST 15 m telescope to observe the central part of the 30 Doradus Nebula (rms ~0.2 K at 0.5 km s^{-1} velocity resolution for J = 1–0 and rms ~1.0 K at 0.5 km s^{-1} velocity resolution for J = 3–2) and the southern H II regions N158C, N159, and N160 with a few prominent CO clouds in the J = 2–1 and J = 3–2 transitions of CO. They find that the kinetic temperatures are 10–80 K and the highest temperature is toward 30 Dor. The smallest beam size and grid spacing are 15^" and 11^" respectively, in the J = 3–2 emission. Heikkilä et al. (1999) used SEST to observe the J = 3–2 transition of CO in N159 and 30 Doradus, as well as other rarer molecular species. This study aimed at obtaining chemical abundances, while it also provides more information on cloud temperature, etc., from CO(J = 3–2) data. The kinetic temperatures that they derived are 50 K in 30 Dor-10, 15 K in 30 Dor-27, and 20–25 K in N159W and N160. Bolatto et al. (2005) employed the AST/RO to observe the 12 CO(J = 4–3) transition at 461 GHz with a 109'' beam. They observed nine regions in the LMC at 6' x 6' field, all with H II regions, and derived kinetic temperatures from a comparison between the CO(J = 4–3) and (J = 1–0) transitions. N48, N55A, N79, N83A, N113, N159W, N167, N214C, and LIRL 648 are included. They derive temperatures of 100–300 K and note a trend that higher temperatures occur in moderate-density regions, 100–1000 cm^{-3}, and the lower temperatures in much denser regions, 10^4–10^5 cm^{-3}. These studies were preceded by a suggestion that significant amounts of warm molecular gas may exist in the LMC (Israel et al. 2003). Kim et al. (2004) also made similar observations toward an H II region, N44, and suggest very dense gas of ~10^5 cm^{-3}. Most recently, Kim (2006) derived T_{kin} = 100 K and n = 10^4.3 cm^{-3} for 30 Dor from the intensity ratios of 12 CO(J = 7–6) to 12 CO(J = 4–3) and 12 CO(J = 1–0) to 12 CO(J = 1–0).

In the present study, we aim to obtain submillimeter molecular data at better signal-to-noise ratios than in the previous studies to make estimates of temperatures and densities over a large sample in the LMC. We combine the 12 CO(J = 3–2) data obtained with the ASTE telescope and CO(J = 1–0) data obtained with the SEST and Mopra telescopes. In order to make reasonable comparisons between the two transitions, J = 3–2 and J = 1–0, we smooth the ASTE results (22'' beam) to the same resolution as the SEST data (45'') and use large velocity gradient (LVG) calculations to estimate density and temperature. We also employ the 12 CO(J = 1–0) data, where available, to place constraints on the physical parameters.

This paper is organized as follows: § 2 describes the observations. Sections 3 and 4 show the results and data analysis, respectively. In § 5, we discuss the physical properties of clumps and evolutionary sequence of GMCs. Finally, we present a summary in § 6.

2. OBSERVATIONS

2.1. Selection of GMCs

The present targets were chosen from the NANTEN catalog of 12 CO(J = 1–0) GMCs compiled by Fukui et al. (2007). This catalog is based on the second survey, with a factor of ~2 higher sensitivity than the first survey (Mizuno et al. 2001). The catalog includes 272 CO clouds, 230 of which are detected at three or more observed positions, and they are classified into the three types: 56 (24.3%) type I (starless) GMCs, 120 (52.2%) type II GMCs (those with H II regions only), and 54 (23.5%) type III GMCs (those with H II regions and young star clusters), where “stars”
In the present study, we observe GMCs in the southeast region of the LMC, which contains 30 Doradus, the largest and most massive \HII region in the Local Group. We observe the molecular ridge extending southward from 30 Doradus and the "CO Arc" along the southeastern optical edge (Fukui et al. 1999). Three type III GMCs, LMC N J0538–6904 (the 30 Dor region), LMC N J0540–7008 (the N159 region and the N171 region), and LMC N J0530–7106 (the N206 region), are selected as the principal targets, and two type II GMCs, LMC N J0544–6923 (the N166 region) and LMC N J0532–7114 (the N206D region), and a type I GMC, LMC N J0547–7041 (the GMC 225 region), are included for reference. The locations of the observed GMCs and regions are shown in Figure 1, and their coordinates and the data used in this paper are summarized in Table 1. Hereafter, the region names, which are in the parentheses above or column (4) of Table 1, are used to identify the regions.

2.2. $^{12}$CO($J = 3–2$)

Observations of the $^{12}$CO($J = 3–2$) transition at 345 GHz were made with the ASTE telescope at Pampa la Bola in Chile (Ezawa et al. 2004) in 2004 October. The half-power beam width was measured to be $22''$ at 345 GHz by observing the planets. This corresponds to 5.3 pc at the distance of the LMC, 50 kpc. The telescope was equipped with a single "cartridge-type" SIS receiver, sensitive from 324 to 384 GHz, which is of a similar design to that for ALMA (Kohno 2005). The spectrometer was an XF-type digital autocorrelator (Sorai et al. 2000) and was used in the wideband mode, which has a bandwidth of 512 MHz with 1024 channels. The spectrometer provided a velocity coverage and resolution of 450 and 0.44 km s$^{-1}$, respectively, at 345 GHz. We observed six GMCs (seven regions) in the Large Magellanic Cloud as shown in Figure 1 and listed in Table 1. These observations were carried out by position switching at a grid spacing of 20$''$ or 30$''$ for the entire clouds and of 10$''$ or 15$''$ for the regions around the local peaks of the integrated intensity. The pointing error was measured to be within 7$''$ in peak to peak by observing CO point sources R Dor or o Cet every 2 hr during this observing term. The spectral intensities were calibrated by employing the standard room-temperature chopper-wheel technique. We observed Ori-KL once a day, and N159W every 2 hr to check the stability of the intensity calibration, and the intensity variation during these observations was less than 13%. We use 0.7 for the main-beam efficiency at 345 GHz, which was measured by

![Fig. 1.—CO velocity-integrated intensity map (Fukui et al. 2001, 2007) overlaid on ESO(R) image. The observed seven regions are indicated by white circles. [See the electronic edition of the Supplement for a color version of this figure.]](image)

### TABLE 1

| GMC | Type | Region Name | Position | Telescope |
|-----|------|-------------|----------|-----------|
| No. | Name | (1)        | (2)      | (3)       | (4) | (5) | (6) | (7) | (8) | (9) | (10) |
| 186 | LMC N J0538–6904 | III | 30 Dor | 39.02 | 69.00 | 1 | ASTE | MOPRA | SEST |
| 197 | LMC N J0540–7008 | III | N159 | 40.18 | 64.70 | 1 | ASTE | MOPRA | SEST |
| 216 | LMC N J0544–6923 | II | N166 | 52.58 | 61.30 | 3 | ASTE | SEST | SED |
| 153 | LMC N J0530–7106 | III | N206 | 31.33 | 71.00 | 4 | ASTE | SEST | SED |
| 156 | LMC N J0532–7114 | II | N206D | 52.22 | 71.60 | 4 | ASTE | SEST | SED |
| 225 | LMC N J0547–7041 | I | GMC 225 | 48.37 | 70.40 | 4 | ASTE | SEST | SED |

Notes.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. Col. (1): Running number of GMC used in Table 1 in Fukui et al. (2007). Col. (2): Name of GMC. Col. (3): Type of GMC. Col. (4): Region name used in this paper. Cols. (5)–(6): Coordinates used as reference position in each region for these $^{12}$CO($J = 3–2$) observations. Col. (7): References for the positions. Cols. (8)–(10): Telescope used for each observation.

References.—(1) Johansson et al. 1998; (2) Kutner et al. 1997; (3) Garay et al. 2002; (4) Mizuno et al. 2001.
observing Jupiter. The system noise temperature was typically 300 K in double-sideband (DSB) including the atmosphere toward the zenith. The typical rms noise fluctuations were ~0.25 K at a velocity resolution of 0.44 km s$^{-1}$ for a 1 minute integration for an on-position. In total, about 1400 points were observed in equatorial coordinates (B1950). Velocities were relative to the local standard of rest (LSR). These observations were made remotely from an ASTE operations room in San Pedro de Atacama, Chile, using the network observation system N-COSMOS3 developed by NAOJ (Kamazaki et al. 2005).

2.3. $^{12}$CO($J = 1-0$) and $^{13}$CO($J = 1-0$)

2.3.1. Mopra Observations

A $20' \times 120'$ region, the prominent molecular ridge extending from 30 Doradus southward, was mapped in the $J = 1-0$ transition of $^{12}$CO at a frequency of 115 GHz with the 22 m ATNF Mopra telescope, in five runs from 2005 May to September. This region contains the 30 Dor, N159, and N171 regions. The newly implemented on-the-fly (OTF) mode was used, in which the telescope takes data continuously while moving across the sky. Spectra were taken at a 6'' spacing so that the 33'' Mopra beam would be well oversampled in the scanning direction; the row spacing was 8'', also assuring oversampling. The typical system noise temperature, $T_{sys}$, was 500 K in the single sideband (SSB) toward the zenith. The pointing was checked on the SiO maser toward R Dor every 2 hr; typical pointing error was less than 5'' with a grid spacing of 20''.

The pointing accuracy was 5'' rms. We checked this by observing the SiO maser toward R Dor every 2 hr during this observing term. N159W was observed periodically for pointing checks and intensity calibration. We use 0.8 for the main-beam efficiency at 115 GHz by assuming the main-beam temperature $T_{mb}$ of N159W to be $-6.5$–$6.9$ K to keep consistency with previous publications (Johansson et al. 1994, 1998).

Observations toward the N166 region were also made using the SEST 15 m telescope. The details are described separately by Garay et al. (2002).

3. RESULTS

We first present the $^{13}$CO($J = 3-2$) images of the clouds at 5 pc resolution and compare them empirically with the $^{12}$CO($J = 1-0$) distribution (§ 3.1). Next, we define molecular clumps and estimate the physical parameters of each clump (§ 3.2).

3.1. Distributions of the $^{12}$CO($J = 3-2$) Emission

In Figure 2, typical $^{12}$CO($J = 3-2$) and $^{12}$CO($J = 1-0$) profiles of the 30 Dor, N159, and GMC 225 regions are presented. The upper panels, Figures 2a–2c, show $^{12}$CO($J = 3-2$) profiles. These illustrate the low noise levels of the present data, typically ~0.25 K rms at 0.44 km s$^{-1}$ velocity resolution. Among the present observed positions, the $^{12}$CO($J = 3-2$) intensity is strongest at $T_{mb} \sim 12.3$ K toward N159W (Fig. 2b). The lower panels, Figures 2d–2f, show $^{12}$CO($J = 1-0$) profiles toward the same positions, where the gray line indicates $^{12}$CO($J = 3-2$) profiles convolved to a 45'' Gaussian beam following the method described in § 4. The $^{12}$CO($J = 3-2$) intensities from the 30 Dor and N159 regions are a little stronger than the $^{12}$CO($J = 1-0$) intensity when convolved to the same resolution. Only toward GMC 225 is the $^{12}$CO($J = 3-2$) intensity about 50% weaker than the $^{12}$CO($J = 1-0$) intensity. The peak velocity and line width are nearly the same between the two transitions in these regions.

The distributions of the integrated intensities of $^{12}$CO($J = 3-2$) and $^{12}$CO($J = 1-0$) are shown in Figures 3–9. Detailed descriptions of each region are presented in the following.

3.1.1. 30 Dor (Fig. 3)

Figures 3a and 3b show the distributions of the $^{12}$CO($J = 3-2$) and $^{12}$CO($J = 1-0$) integrated intensities in the 30 Dor region. We see a general trend that the $J = 3-2$ distribution shows more details that are not obvious in the $J = 1-0$ distribution owing to the higher angular resolution and possibly due to the more compact distribution of warmer and denser gas in $J = 3-2$ than in $J = 1-0$. We see three peaks corresponding to the $^{12}$CO($J = 1-0$) peaks, 30 Dor-10, 30 Dor-6, and 30 Dor-12, reported in Johansson et al. (1998). One of them in the north, 30 Dor-06, which is singly peaked in $J = 1-0$, appears to be resolved into two peaks with the present beam.

3.1.2. N159 (Fig. 4)

Figures 4a and 4b show the $^{12}$CO($J = 3-2$) and $^{12}$CO($J = 1-0$) distributions in N159. We note that N159W shows the strongest intensity among the present clouds, as well as a very compact peak that is not sufficiently resolved with the present beam. Its radius is estimated to be a few parsecs after deconvolution. N159E also shows a compact distribution with a hint of a subpeak, while N159S shows similar distributions in both $J = 1-0$ and $J = 3-2$. 

3.2. SEST Observations

Observations toward the N206, N206D, and GMC 225 regions in the $^{12}$CO($J = 1-0$) line (115 GHz) were made in 2001 August and 2002 February using the SEST 15 m telescope at La Silla, Chile. The HPBW was 45'' at 115 GHz, the front end was the IRAM 115 SIS receiver, and the spectrometer was a high-resolution AOS with 2048 channels. The typical system noise temperature was 550 K (SSB). The velocity resolution and coverage were 0.2 and 216 km s$^{-1}$, respectively, at 115 GHz. We mapped these three regions in position switching with a grid spacing of 40'' or 20''. The typical integration time was 1 minute for an on-position, providing rms noise fluctuations of ~0.18 K at a velocity resolution of 0.2 km s$^{-1}$.

Observations toward the N206, N206D, and GMC 225 regions in the $^{13}$CO($J = 1-0$) line (110 GHz) were made in 2002 February and December 2002, also using the SEST 15 m telescope. We mapped peak positions of $^{12}$CO($J = 1-0$) in position switching with a grid spacing of 20''. The system noise temperature was typically 230 K (SSB). The typical integration time was 4 minutes for an on-position, providing rms noise fluctuations of ~0.04 K at a velocity resolution of 0.2 km s$^{-1}$.

The pointing accuracy was 5'' rms. We checked this by observing the SiO maser toward R Dor every 2 hr during this observing term. N159W was observed periodically for pointing checks and intensity calibration. We use 0.8 for the main-beam efficiency at 115 GHz by assuming the main-beam temperature $T_{mb}$ of N159W to be $-6.5$–$6.9$ K to keep consistency with previous publications (Johansson et al. 1994, 1998).

Observations toward the N166 region were also made using the SEST 15 m telescope. The details are described separately by Garay et al. (2002).
The east-west elongation of N159S may be due to the scanning effect of the OTF mapping and needs to be confirmed.

3.1.3. N171 (Fig. 5)  
Figures 5a and 5b show the $^{12}$CO($J = 3–2$) and $^{12}$CO($J = 1–0$) distributions in N171. We note that the $J = 3–2$ emission is weaker than the $J = 1–0$ emission. There are multiple velocity components, at $V_{LSR} = 225, 230,$ and $240$ km s$^{-1}$ in both $J = 3–2$ and $J = 1–0$ as indicated in Table 2 and Table 1 of Kutner et al. (1997).

3.1.4. N166 (Fig. 6)  
Figures 6a and 6b show the $^{12}$CO($J = 3–2$) and $^{12}$CO($J = 1–0$) distributions in N166. The $J = 1–0$ data themselves have already been published by Garay et al. (2002). We see four peaks in both $J = 3–2$ and $J = 1–0$. Of these peaks, three peaks are named Cloud-B, Cloud-C, and Cloud-D, as reported by Garay et al. (2002), although Cloud-C is resolved into two peaks with the present beam and observing grid.

3.1.5. N206 (Fig. 7)  
Figures 7a and 7b show the $^{12}$CO($J = 3–2$) and $^{12}$CO($J = 1–0$) distributions in N206. A $J = 1–0$ peak appears to be resolved into two subpeaks and a north-south filamentary structure with the higher angular resolution of the $J = 3–2$ line.

3.1.6. N206D (Fig. 8)  
Figures 8a and 8b show the $^{12}$CO($J = 3–2$) and $^{12}$CO($J = 1–0$) distributions in N206D. We can see a head-tail structure in $J = 3–2$, although it appears more rounded in $J = 1–0$.

3.1.7. GMC 225 (Fig. 9)  
Figures 9a and 9b show the $^{12}$CO($J = 3–2$) and $^{12}$CO($J = 1–0$) distributions in GMC 225. We note that $J = 3–2$ emissions are weaker than those of $J = 1–0$.

3.2. Properties of the Clumps  
We identified clumps in the following way in the $J = 3–2$ distributions shown in Figures 3–9: (1) Pick up local peaks using the integrated intensity. (2) Draw a contour at one-half the peak
integrated intensity level and identify it as a clump unless it contains other local peaks. (3) When there are other local peaks inside the contour, draw new contours at the 70% level of each integrated intensity peak. Then, identify clumps separately if their contours do not contain another local peak (the boundary is taken at the "valley" between clumps), or else identify a clump by using the highest contour as a clump boundary. (4) If a spectrum has multiple "valleys" between clumps, or else identify a clump by using the strength of the peak instead of the 50% level, the clump size changes. Their virial mass also changes to about one-half the original one. Histograms of their physical properties are presented in Figure 18. The averaged $R_{3-2/1-0}$ over each clump (hereafter, $R_{3-2/1-0,\text{clump}}$) was also derived from the averaged $^{12}\text{CO}(J=3-2)$ and $^{12}\text{CO}(J=1-0)$ spectra over each clump. A summary of the $R_{3-2/1-0,\text{clump}}$ for each clump is shown in Table 4. The histogram in Figure 18 shows that the $R_{3-2/1-0,\text{clump}}$ ranges from 0.2 to 1.6. These ratios will be compared with numerical calculations of radiative transfer in the LVG approximation to derive constraints on density and temperature.

4.2. LVG Analysis

4.2.1. Calculations of LVG Model

To estimate the physical properties of the molecular gas in the LMC, we performed an LVG analysis (Goldreich & Kwan 1974) of the CO rotational transitions. The LVG radiative transfer code simulates a spherically symmetric cloud of constant density and temperature with a spherically symmetric velocity distribution proportional to the radius and employs a Castor escape probability formalism (Castor 1970). It solves the equations of statistical equilibrium for the fractional population of CO rotational levels

are based on optically thin millimeter dust continuum and C^{18}O emission. The clumps in the LMC are also fairly compact, with sizes of several parsecs or less. Hereafter, the region names and the numbers of clumps are used to identify clumps (e.g., "30 Dor No. 1")

4. DATA ANALYSIS

4.1. Derivation of Line Intensity Ratios

The spatial resolution of the present CO data varies depending on the telescope and frequency. We convolved and regressed these data into the same resolution and position using two-dimensional Gaussian smoothing in order to compare them to derive reliable peak intensity ratios of $^{12}\text{CO}(J=3-2)$ to $^{12}\text{CO}(J=1-0)$ (hereafter, $R_{3-2/1-0}$).

We made Gaussian fits to each of the $^{12}\text{CO}(J=3-2)$ and $^{12}\text{CO}(J=1-0)$ spectra having a single peak in most cases. We derived peak intensities and FWHM line widths through these fittings. The ratios of the two transitions were then derived as the ratio between peak values of $T_{mb}$. The distributions of these ratios are shown along with the $^{12}\text{CO}(J=1-0)$ distributions in panels (a) of Figures 11–17. The youngest stellar clusters SWB0, whose ages are estimated to be less than 10 Myr, are also shown by gray or black circles (Bica et al. 1996).

The averaged $R_{3-2/1-0}$ over each clump (hereafter, $R_{3-2/1-0,\text{clump}}$) was also derived from the averaged $^{12}\text{CO}(J=3-2)$ and $^{12}\text{CO}(J=1-0)$ spectra over each clump. A summary of the $R_{3-2/1-0,\text{clump}}$ for each clump is shown in Table 4. The histogram in Figure 18 shows that the $R_{3-2/1-0,\text{clump}}$ ranges from 0.2 to 1.6. These ratios will be compared with numerical calculations of radiative transfer in the LVG approximation to derive constraints on density and temperature.
| Region       | No. | α(1950) | δ(1950) | \( T_{\text{mb}} \) | \( V_{\text{LSR}} \) | \( \Delta V' \) | Integrated Intensity | Other ID    |
|--------------|-----|---------|---------|-----------------|-----------------|-----------------|---------------------|-------------|
|              |     |         |         | (K)             | (km s\(^{-1}\)) | (km s\(^{-1}\)) | (K km s\(^{-1}\)) |             |
| 30 Dor       | 1   | 5 39 8.6 | −69 6 15 | 5.2             | 250.4           | 8.4             | 49.5                | 30Dor-10\(^a\) |
|              | 2   | 5 38 54.6 | −69 8 0  | 4.3             | 246.9           | 6.9             | 31.7                | 30Dor-12\(^a\) |
|              | 3   | 5 38 49.0 | −69 4 30 | 3.1             | 251.9           | 5.4             | 22.5                |             |
|              | 4   | 5 38 49.0 | −69 3 30 | 2.6             | 248.2           | 5.0             | 21.1                | 30Dor-06\(^a\) |
|              | 5   | 5 38 54.6 | −69 9 0  | 1.2             | 247.4           | 4.5             | 5.3                 |             |
| N159         | 1   | 5 40 3.7  | −69 47 0 | 12.3            | 237.3           | 8.1             | 106.6               | N159-W\(^a\) |
|              | 2   | 5 40 35.5 | −69 46 0 | 7.6             | 233.2           | 7.0             | 55.5                | N159-E\(^a\) |
|              | 3   | 5 40 47.1 | −69 46 15| 5.4             | 234.6           | 6.7             | 46.0                |             |
|              | 4   | 5 40 32.7 | −69 52 0 | 3.5             | 234.4           | 9.7             | 35.4                |             |
|              | 5   | 5 39 49.3 | −69 47 0 | 3.0             | 233.5           | 9.5             | 29.7                |             |
|              | 6   | 5 40 47.2 | −69 51 30| 3.6             | 235.6           | 5.3             | 19.8                |             |
|              | 7   | 5 39 55.1 | −69 45 0 | 4.5             | 238.3           | 3.4             | 16.6                |             |
|              | 8   | 5 40 29.8 | −69 50 0 | 0.91            | 234.6           | 6.9             | 10.5                |             |
|              | 9   | 5 40 41.4 | −69 51 0 | 0.87            | 235.7           | 8.0             | 9.3                 |             |
|              | 10  | 5 39 37.7 | −69 45 30| 0.89            | 238.6           | 7.9             | 8.3                 |             |
| N171         | 1   | 5 40 0.5  | −70 12 30| 2.5             | 224.3           | 5.2             | 15.4                | 30DOR-CENTER-04\(^b\) |
|              | 2   | 5 40 0.5  | −70 10 30| 1.3             | 227.3           | 8.3             | 12.7                |             |
|              | 3   | 5 40 24.1 | −70 12 30| 1.3             | 230.9           | 9.2             | 18.2                |             |
|              | 4   | 5 40 24.1 | −70 12 30| 2.3             | 231.0           | 6.7             | 16.1                |             |
|              | 5   | 5 40 6.4  | −70 9 0  | 1.7             | 240.6           | 4.9             | 11.5                |             |
|              | 6   | 5 40 18.2 | −70 9 30 | 1.9             | 240.7           | 5.1             | 10.4                |             |
| N166         | 1   | 5 44 58.2 | −69 26 39| 4.5             | 227.6           | 4.5             | 22.1                | Cloud-C\(^e\) |
|              | 2   | 5 44 46.8 | −69 27 24| 2.9             | 229.4           | 6.2             | 20.3                |             |
|              | 3   | 5 45 3.9  | −69 29 9 | 2.2             | 227.9           | 5.5             | 14.6                | Cloud-D\(^e\) |
|              | 4   | 5 44 32.6 | −69 23 39| 1.0             | 236.1           | 9.2             | 10.1                | Cloud-B\(^e\) |
|              | 5   | 5 45 9.6  | −69 30 9 | 0.82            | 231.6           | 4.5             | 9.6                 |             |
| N206         | 1   | 5 31 29.8 | −71 9 40 | 5.1             | 229.0           | 4.6             | 26.2                |             |
|              | 2   | 5 31 46.3 | −71 8 20 | 2.5             | 231.2           | 4.6             | 13.5                |             |
| N206D        | 1   | 5 32 58.4 | −71 15 20| 4.5             | 224.6           | 4.0             | 18.9                |             |
| GMC 225      | 1   | 5 47 51.3 | −70 41 20| 1.8             | 216.5           | 3.9             | 9.0                 |             |
|              | 2   | 5 48 25.6 | −70 41 20| 1.2             | 216.2           | 6.2             | 8.6                 |             |
|              | 3   | 5 48 53.9 | −70 40 30| 1.8             | 216.4           | 3.8             | 7.9                 |             |

Notes.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. Col. (1): Region. Col. (2): Running number in each region. Cols. (3)–(4): Positions of observed points with maximum \(^{12}\)CO\((J = 3\rightarrow 2)\) integrated intensities within the \(^{12}\)CO\((J = 3\rightarrow 2)\) clumps given in equatorial coordinates. Cols. (5)–(8): Observed properties of the \(^{12}\)CO\((J = 3\rightarrow 2)\) spectra obtained at the peak positions of the \(^{12}\)CO\((J = 3\rightarrow 2)\) clumps. The peak main-beam temperature \(T_{\text{mb}}\), \(V_{\text{LSR}}\), and the FWHM line width \(\Delta V'\) are derived from a single Gaussian fitting and are given in cols. (5), (6), and (7), respectively. In col. (8), the \(^{12}\)CO\((J = 3\rightarrow 2)\) integrated intensities at the peak positions of the \(^{12}\)CO\((J = 3\rightarrow 2)\) clumps are shown. Col. (9): Another identification based on \(^{12}\)CO\((J = 1\rightarrow 0)\) observations with SEST.

\(^a\) Johansson et al. (1998).
\(^b\) Kutner et al. (1997).
\(^c\) Garay et al. (2002).
at each density and temperature. It includes the lowest 40 rotational levels of the ground vibrational level and uses the Einstein A and H₂ impact rate coefficients of Schönier et al. (2005).

The present calculations incorporate the lowest 40 rotational levels of CO in the ground vibrational state over a kinetic temperature range of \( T_{\text{kin}} = 5 \sim 200 \) K and a density range of \( n(H_2) = 10^{-10} \text{ cm}^{-3} \). We did not include higher energy levels in the present study, which requires including populations in the lower vibrationally excited states. Therefore, the present work does not cover kinetic temperatures above 200 K, which should be dealt with in the future for analyses of higher submillimeter transitions above \( J = 4 \sim 3 \). This imposes a limit of \( T_{\text{kin}} \sim 200 \) K in the present study, and even higher temperature is not excluded in general below.

We performed calculations for three different CO fractional abundances: \( X(\text{CO}) = [\text{CO}] / [\text{H}_2] = 1 \times 10^{-6}, 3 \times 10^{-6}, \) and \( 1 \times 10^{-5} \), and three different \( ^{12}\text{CO}/^{13}\text{CO} \) abundance ratios of 20, 25, and 30 (Heikkilä et al. 1999).

4.2.2. Results from \( ^{12}\text{CO}(J = 3\sim 2) \) and \( ^{12}\text{CO}(J = 1\sim 0) \)

Data for 32 Clumps

First, we assume that \( X(\text{CO}) \) is uniform among the clumps and derive density and temperature using the LVG results. Figure 19a illustrates that we obtain the following lower limits for kinetic temperature and density. For the eight clumps with \( R_{3,\sim 2\sim 1;\sim 0} / \text{clump} \geq 1 \) (30 Dor Nos. 1, 2, 3, 4; N159 Nos. 1, 2, 6, 8), we estimate \( T_{\text{kin}} > 30 \) K and \( n(H_2) > 10^{12} \text{ cm}^{-3} \). For the 24 clumps with \( R_{3,\sim 2\sim 1;\sim 0} / \text{clump} < 1 \) (30 Dor No. 5, N159 Nos. 3, 4, 5, 7, 9, 10, N171 Nos. 1, 2, 3, 4, 5, 6, N166 Nos. 1, 2, 3, 4, 5, N206 Nos. 1, 2, N206D No. 1, GMC 225 Nos. 1, 2, 3), we estimate \( T_{\text{kin}} \) greater than several kelvins and \( n(H_2) \) greater than several times \( 10^2 \text{ cm}^{-3} \). In either case, the lower limits tend to increase with \( R_{3,\sim 2\sim 1;\sim 0} / \text{clump} \).

4.2.3. Results from \( ^{13}\text{CO}(J = 3\sim 2) \), \( ^{13}\text{CO}(J = 1\sim 0) \), and \( ^{13}\text{CO}(J = 1\sim 0) \) Data for 13 Clumps

We can better constrain these physical parameters when \(^{13}\text{CO}(J = 1\sim 0)\) data are available. Figure 19 shows the general behavior of the loci of constant \( R_{3,\sim 2\sim 1;\sim 0} / \text{clump} \) and constant \( R_{12/13} \) [peak intensity ratio of \(^{12}\text{CO}(J = 1\sim 0)\) to \(^{13}\text{CO}(J = 1\sim 0)\)] in the density-temperature plane. It is recognized that the combination of the two will allow us to determine the parameters relatively well, since the two lines are nearly “orthogonal” in the plane, except for densities higher than \( \sim 10^4 \text{ cm}^{-3} \) (Fig. 19).
Of the 32 clumps, $^{13}$CO($J = 1-0$) data are available for 13 clumps, including four clumps with $R_{\text{deconv}} = ](30 \text{ Dor Nos. } 1, 4, N159 \text{ Nos. } 1, 2)$ and nine clumps with $R_{\text{deconv}} < 1$ (N159 No. 4, N166 Nos. 1, 3, 4, N206 Nos. 1, 2, N206D No. 1, GMC 225 Nos. 1, 3). For these 13 clumps, we made a detailed analysis using the $R_{\text{deconv}}$ at peaks of $^{12}$CO($J = 1-0$) and have obtained the best constraints.

We summarize the input parameters for the 13 clumps in columns (3)–(5) of Table 5. All the data refer to the $^{12}$CO($J = 1-0$) beam size, 45"; the higher transition data have been Gaussian smoothed as described in § 4.1. Clump-averaged $dv/dr$ were used for the calculations. The $R_{3-2/1-0}$, and $R_{12/13}$ at the peak of $^{12}$CO($J = 1-0$) were used, and the errors of these ratios are both estimated as ±20%, which are derived from errors of absolute intensity calibration. These correspond to 27 σ and 7 σ noise levels of $^{12}$CO($J = 3-2$) and $^{12}$CO($J = 1-0$), respectively. This indicates that the errors of the intensity ratios are dominated by the error of the absolute intensity calibration.

Of the 32 clumps, $^{13}$CO($J = 1-0$) data are available for 13 clumps, including four clumps with $R_{\text{deconv}} = 30$ Dor Nos. 1, 4, N159 Nos. 1, 2) and nine clumps with $R_{\text{deconv}} < 1$ (N159 No. 4, N166 Nos. 1, 3, 4, N206 Nos. 1, 2, N206D No. 1, GMC 225 Nos. 1, 3). For these 13 clumps, we made a detailed analysis using the $R_{\text{deconv}}$ at peaks of $^{12}$CO($J = 1-0$) and have obtained the best constraints.

We summarize the input parameters for the 13 clumps in columns (3)–(5) of Table 5. All the data refer to the $^{12}$CO($J = 1-0$) beam size, 45"; the higher transition data have been Gaussian smoothed as described in § 4.1. Clump-averaged $dv/dr$ were used for the calculations. The $R_{3-2/1-0}$, and $R_{12/13}$ at the peak of $^{12}$CO($J = 1-0$) were used, and the errors of these ratios are both estimated as ±20%, which are derived from errors of absolute intensity calibration. These correspond to 27 σ and 7 σ noise levels of $^{12}$CO($J = 3-2$) and $^{12}$CO($J = 1-0$), respectively. This indicates that the errors of the intensity ratios are dominated by the error of the absolute intensity calibration. The way clumps are
Fig. 11.—(a) Color map of $R_3$, and (b) Hα flux image of the 30 Doradus region. Contours are $^{12}$CO($J = 3$–$2$) integrated intensity. Contour levels are the same as in Fig. 3a. Thick lines indicate observed area in $^{12}$CO($J = 3$–$2$); gray circle indicates position of young cluster (<10 Myr; SWB0). [See the electronic edition of the Supplement for a color version of this figure.]

Fig. 12.—(a) Color map of $R_3$, and (b) Hα flux image of the N159 region. Contours are $^{12}$CO($J = 3$–$2$) integrated intensity. Contour levels are the same as in Fig. 4a. Thick lines indicate observed area of $^{12}$CO($J = 3$–$2$); black circles indicate positions of young clusters (<10 Myr; SWB0). [See the electronic edition of the Supplement for a color version of this figure.]

Fig. 13.—(a) Color map of $R_3$, and (b) Hα flux image of the N171 region. Contours are $^{12}$CO($J = 3$–$2$) integrated intensity. Contour levels are the same as in Fig. 5a. Thick lines indicate observed area of $^{12}$CO($J = 3$–$2$). [See the electronic edition of the Supplement for a color version of this figure.]

Fig. 14.—(a) Color map of $R_3$, and (b) Hα flux image of the N166 region. Contours are $^{12}$CO($J = 3$–$2$) integrated intensity. Contour levels are the same as in Fig. 6a. Thick lines indicate observed area of $^{12}$CO($J = 3$–$2$). [See the electronic edition of the Supplement for a color version of this figure.]

Fig. 15.—(a) Color map of $R_3$, and (b) Hα flux image of the N206 region. Contours are $^{12}$CO($J = 3$–$2$) integrated intensity. Contour levels are the same as in Fig. 7a. Thick lines indicate observed area of $^{12}$CO($J = 3$–$2$). [See the electronic edition of the Supplement for a color version of this figure.]

Fig. 16.—(a) Color map of $R_3$, and (b) Hα flux image of the N206D region. Contours are $^{12}$CO($J = 3$–$2$) integrated intensity. Contour levels are the same as in Fig. 8a. Thick lines indicate observed area of $^{12}$CO($J = 3$–$2$). [See the electronic edition of the Supplement for a color version of this figure.]
defined does not change $R_{3-2/1-0}$clump but changes $dv/dr$, and $dv/dr$ is about 2 times as large as the original one, when the clumps are identified with the 70% level of the peak integrated intensity level. This, however, does not affect the results of the LVG calculations.

We describe three typical cases: (a) 30 Dor No. 1, (b) N206 No. 1, and (c) GMC 225 No. 1. In Figure 20. A fractional CO abundance of $X(Y)$ without 30 Dor was used throughout. The horizontal axis is molecular hydrogen density $n(H_2)$, and the vertical axis is the gas kinetic temperature ($T_{kin}$). Solid lines represent $R_{3-2/1-0}$clump, and the clumps are identified with the 70% level of the peak integrated intensity level. Hatched areas indicate the overlap regions of these two ratios within the errors, which is allowed from the observed ratios. It also includes the uncertainty due to a possible variation of the $CO/12CO$ abundance ratio from 20 to 30. Hereafter, we call clumps above 30 K "warm" and those below "cold." Clumps that we detected are distributed continuously from cool ($\sim 10$–30 K) to warm ($\sim$higher than 30–200 K), and warm clumps are distributed from less dense ($\sim 10^2$ cm$^{-3}$) to dense ($\sim 10^5$–$10^5$ cm$^{-3}$), although cool clumps are all less dense. The three cases shown in Figure 20 represent typical cases, "warm and dense" [$T_{kin} \geq 30–200$ K, $n(H_2) \sim 10^3–10^5$ cm$^{-3}$], "warm and less dense" [$T_{kin} \geq 30–200$ K, $n(H_2) \sim 10^3$ cm$^{-3}$], and "cool and less dense" [$T_{kin} \sim 10–30$ K, $n(H_2) \sim 10^3$ cm$^{-3}$].

4.2.4. Effects of $X(CO)$

We now discuss the possible effect of changing $X(CO)$, as summarized in Table 6. If we adopt $X(CO) = 1 \times 10^{-6}$, the contours of $R_{3-2/1-0}$ shift to lower temperature and the contours of $R_{12/13}$ shift to higher density. Accordingly, the solution shifts to lower temperature, higher density. If we adopt $X(CO) = 1 \times 10^{-5}$, the $R_{3-2/1-0}$ contours shift to higher temperature and the $R_{12/13}$ contours shift to lower density. Accordingly, the solution shifts to higher temperature, lower density (Table 6).

Next, we vary $X(CO)$ from clump to clump. Heikkinen et al. (1999) estimate $X(CO)$ for 30 Dor No. 1 (30 Dor-10), N159 No. 1 (N159W), and N159 No. 4 (N159S) to be $1 \times 10^{-6}$, $1 \times 10^{-5}$, and $3 \times 10^{-6}$, respectively. Table 6 indicates that 30 Dor No. 1 shows similar values to Heikkinen et al. (1999) whereas N159 No. 1 and No. 4 become warmer and lower in density than in Heikkinen et al. (1999). This discrepancy may be due to the fact that the high-density tracers used by Heikkinen et al. (1999) are not used in the present study. To summarize, the assumption of uniform fractional abundance, $X(CO)$, is fairly good and the present results do not show significant difference even if we adopt the different fractional abundances used by previous authors.

4.3. Comparisons to H$\alpha$ Flux

4.3.1. Relation between $R_{3-2/1-0}$ and H$\alpha$ Flux

We converted the H$\alpha$ data (Kim et al. 1999) toward the present clouds using the method given in Appendix B. The typical background level of the H$\alpha$ flux is $\sim 10^{-12}$ ergs s$^{-1}$ cm$^{-2}$ at the 40" scale and ranges up to $10^{-10}$ ergs s$^{-1}$ cm$^{-2}$ toward strong H II regions (Fig. 22). These data were regridded into the $CO(J = 3–2)$ data grids. H$\alpha$ flux images with the youngest stellar clusters SWB0 (Bica et al. 1996; younger than 10 Myr) are shown in panels (b) of Figures 11–17, and the $CO(J = 3–2)$ contours from Figures 3–9 are overlaid for comparison in these figures.

Figures 11–17 indicate a clear trend that the $R_{3-2/1-0}$ is enhanced to 1.0–1.5 toward H II regions or clouds with young clusters, as in the 30 Dor and N159 regions. On the other hand, the ratio is lower, less than 1.0, toward clumps with neither H II regions nor clusters, as in GMC 225. We also note that the ratio is enhanced toward the regions where H$\alpha$ is intense or toward the interfaces between clouds and H II regions. A summary of the averaged H$\alpha$ flux over each clump is shown in Table 4. It is not fully guaranteed that the H$\alpha$ emission is actually in contact with the molecular gas, and some of the apparent coincidence could be fortuitous. Nonetheless, previous studies comparing CO and H$\alpha$ flux indicate a strong correlation between them and lend support to the assumption that almost all the coincidences indicate an actual physical association (Fukui et al. 1999; Yamaguchi et al. 2001; A. Kawamura et al. 2008, in preparation).

Figure 23 shows the correlation between $R_{3-2/1-0}$clump and the averaged H$\alpha$ flux over each clump. It is clear that $R_{3-2/1-0}$clump is well correlated with the averaged H$\alpha$ flux, with a correlation coefficient of $\sim 0.79$. This is a fairly good empirical relationship and should be tested to see if it holds true in other galaxies. The
### TABLE 4

$^{12}\text{CO}(J = 3–2)/^{12}\text{CO}(J = 1–0)$ Ratio and Hα Flux

| Region         | No. | $T_{mb}(3–2)$ (K) | $T_{mb}(1–0)$ (K) | $R_{3–2}/1–0$,clump | Averaged Hα Flux ($×10^{-12}$ ergs s$^{-1}$ cm$^{-2}$) |
|----------------|-----|-------------------|-------------------|---------------------|---------------------------------|
| 30 Dor.......... | 1   | 1.63              | 1.20              | 1.4                 | 56.49                           |
|                | 2   | 1.76              | 1.12              | 1.6                 | 73.37                           |
|                | 3   | 1.56              | 1.13              | 1.2                 | 24.09                           |
|                | 4   | 1.98              | 1.58              | 1.3                 | 12.83                           |
|                | 5   | 0.73              | 0.87              | 0.8                 | 39.71                           |
| N159............ | 1   | 5.50              | 5.04              | 1.1                 | 9.28                            |
|                | 2   | 3.69              | 3.34              | 1.1                 | 9.37                            |
|                | 3   | 2.92              | 3.25              | 0.9                 | 6.36                            |
|                | 4   | 2.33              | 3.34              | 0.7                 | 1.14                            |
|                | 5   | 1.84              | 2.19              | 0.8                 | 1.93                            |
|                | 6   | 1.61              | 1.57              | 1.0                 | 1.42                            |
|                | 7   | 1.67              | 1.98              | 0.9                 | 3.14                            |
|                | 8   | 0.78              | 0.57              | 1.4                 | 1.52                            |
|                | 9   | 0.80              | 0.99              | 0.8                 | 1.26                            |
|                | 10  | 0.57              | 0.84              | 0.7                 | 1.42                            |
| N171............ | 1   | 1.04              | 2.20              | 0.5                 | 1.00                            |
|                | 2   | 0.69              | 1.55              | 0.4                 | 0.93                            |
|                | 3   | 1.02              | 3.09              | 0.3                 | 0.97                            |
|                | 4   | 1.34              | 3.89              | 0.3                 | 0.98                            |
|                | 5   | 0.88              | 1.92              | 0.4                 | 0.95                            |
|                | 6   | 0.87              | 2.72              | 0.3                 | 0.97                            |
| N166............ | 1   | 1.97              | 3.09              | 0.6                 | 1.05                            |
|                | 2   | 1.59              | 2.60              | 0.6                 | 1.01                            |
|                | 3   | 1.17              | 1.92              | 0.6                 | 1.06                            |
|                | 4   | 0.79              | 1.26              | 0.6                 | 1.31                            |
|                | 5   | 0.62              | 0.92              | 0.7                 | 1.06                            |
| N206............ | 1   | 1.83              | 2.39              | 0.8                 | 3.26                            |
|                | 2   | 1.34              | 2.44              | 0.5                 | 2.68                            |
| N206D........... | 1   | 2.26              | 4.70              | 0.5                 | 1.11                            |
| GMC 225......... | 1   | 1.04              | 2.81              | 0.4                 | 0.93                            |
|                | 2   | 0.55              | 1.62              | 0.3                 | 0.91                            |
|                | 3   | 0.77              | 2.09              | 0.4                 | 0.92                            |

**Notes.**—Col. (1): Region. Col. (2): Running number in each region. Col. (3): The peak main-beam temperature, $T_{mb}$, of the $^{12}\text{CO}(J = 3–2)$ spectra derived by using a single Gaussian fitting for a spectrum obtained by averaging all the spectra to the beam within a single clump. The intensities refer to the $^{12}\text{CO}(J = 1–0)$ beam size (45′′). Col. (4): Peak main-beam temperature, $T_{mb}$, of the $^{12}\text{CO}(J = 1–0)$ spectra derived by using a single Gaussian fitting for a spectrum obtained by averaging all the spectra within a single clump. Col. (5): Ratios of $T_{mb}(3–2)$ to $T_{mb}(1–0)$. Col. (6): Hα flux obtained by averaging within a single clump.
relation suggests that higher $R_{3-2/1-0} \approx 1.0-1.5$. In the barred spiral galaxy M83, the $\text{CO}(J = 3-2)/(J = 1-0)$ integrated intensity ratio exceeds unity at the nucleus, whereas the ratio gradually decreases to 0.6–0.7 with distance from the center. The ratio is constant through the disk region (Muraoka et al. 2007).

4.3.2. Comparison with Physical Properties and $\text{H} \alpha$ Emission

Figure 24 shows plots of density and temperature as functions of averaged $\text{H} \alpha$ flux and gives us another insight into these properties. Where averaged $\text{H} \alpha$ is strong ($10^{-11}$ ergs s$^{-1}$ cm$^{-2}$) the clumps are always warm, at around $T_{\text{kin}} = 100$ K or more. On the other hand, when averaged $\text{H} \alpha$ is weak, density is always low but temperature can be either high or low.

The high-density clumps show high $R_{3-2/1-0,\text{clump}} \approx 1.0-1.5$ and are associated with strong $\text{H} \alpha$ flux, while the low-density clumps show low $R_{3-2/1-0,\text{clump}} \approx 0.5-1.0$ with weak $\text{H} \alpha$ flux.

Since we are averaging the $\text{H} \alpha$ intensity in each clump, we may be diluting the localized low $\text{H} \alpha$ flux toward some of the clumps in type III and II GMCs. The effects of $\text{H} \alpha$ emission or nearby clusters on the molecular gas are perhaps local phenomena as indicated by the comparison in Figures 11–17 for the individual clumps.

5. DISCUSSIONS

5.1. Dense and Compact Clumps as Candidates for Protocluster Condensations

We have carried out submillimeter $^{12}\text{CO}(J = 3-2)$ observations of GMCs in the LMC that are most extensive and highly sensitive compared to the previous studies. Six GMCs were selected based on the NANTEN CO survey of the LMC, including three type III GMCs actively forming O stars, in addition to three type I/II GMCs that are quiet in O star formation or cluster formation, although the formation of low- to intermediate-mass stars is not excluded. The spatial resolution of $\approx 5$ pc and the high sensitivity allowed us to identify 32 molecular clumps in these GMCs and to reveal significant details of the warm and dense molecular gas with $n(\text{H}_2) \approx 10^3$–$10^7$ cm$^{-3}$ and $T_{\text{kin}} \approx 10$–$200$ K.

The typical mass of the molecular clumps is large, in the range of $5 \times 10^4$ to $2 \times 10^5$ $M_\odot$ with radii of $1$–$12$ pc. Of all of our objects, N159 No. 1 or W shows the strongest concentration of mass of $\approx 7 \times 10^4$ $M_\odot$ within a radius of $\approx 5$ pc. These masses seem to be larger than those of typical Milky Way GMCs such as those in the $\eta$ Car region (e.g., Yonekura et al. 2005), although the properties of these Galactic GMCs are based on optically thin $\text{C}^{18}\text{O}$ data. We suggest that these are good candidates for the precursors of rich superclusters like R136 in 30 Dor, which includes more than $10^4$ stars in a small volume with a radius of $\approx 1$ pc. It is of particular interest to look for even denser gas toward them in higher excitation transitions of the submillimeter region.

5.2. Density and Temperature of the Clumps and Implications

The results of our LVG analysis indicate that clumps are distributed from cool to warm in temperature and from less dense to dense in density. These differences of clump properties in density and temperature show good correspondence with the GMC types based on the star formation activity, as well as with the $\text{H} \alpha$ emission of ionized gas associated with each clump. Clumps in type III GMCs are warm ($T_{\text{kin}} \approx 30$–$200$ K) and are either dense [$n(\text{H}_2) \approx 10^3$–$10^5$ cm$^{-3}$] or less dense [$n(\text{H}_2) \approx 10^5$ cm$^{-3}$]. Clumps in type II GMCs are either warm ($T_{\text{kin}} \approx 30$–$200$ K) or cool ($T_{\text{kin}} \approx 10$–$30$ K) and less dense [$n(\text{H}_2) \approx 10^3$ cm$^{-3}$]. Clumps in type I GMCs are cool ($T_{\text{kin}} \approx 10$–$30$ K) and less dense [$n(\text{H}_2) \approx 10^3$ cm$^{-3}$]. The physical parameters of clumps are

![Image of contour plots](image-url)

**Fig. 18.**—Histogram of clump-averaged peak intensity ratio of $^{12}\text{CO}(J = 3-2)$ to $^{12}\text{CO}(J = 1-0)$ ($R_{3-2/1-0,\text{clump}}$).

**Fig. 19.**—Contour plots of LVG analysis for reference. Contours are (a) $R_{3-2/1-0}$, (b) $R_{12/13}$, and (c) $a + b$. Here $X(\text{CO}) = 3 \times 10^{-6}$, $dv/dr = 1.0$ km s$^{-1}$ pc$^{-1}$, and the abundance ratio of $^{12}\text{CO}/^{13}\text{CO}$ is 25.
## Summary of LVG and Mean Escape Probability Analyses

| Region | No. | $dH_2/de$ (km s$^{-1}$ pc$^{-1}$) | $R_{3,2/1-0,clump}$ (4) | $R_{12/13}$ | This Work | J98 | H99 | B05 SC | B05 CDC | B05 HTC | K06 |
|--------|-----|---------------------------------|--------------------------|-------------|------------|-----|-----|--------|--------|--------|-----|
| 30 Dor | 1   | 0.9                             | 1.4                      |             | 11.5 J98  | 3 x 10$^3$ to 3 x 10$^5$ >50 | 10$^{4.5}$ | 40-80 1 x 10$^5$ 50 | 10$^{4.3}$ | 100 |
|        | 4   | 0.5                             | 1.3                      |             | 17.7 J98  | 1 x 10$^5$ to 1 x 10$^5$ >60 | 10$^{4.5}$ | >20    |        |       |
| N159   | 1   | 0.9                             | 1.1                      |             | 8.6 J98   | 3 x 10$^3$ to 8 x 10$^3$ >30 | 10$^{4.5}$ | 16-23 3 x 10$^5$ 25 10$^5$ 150 | 10$^5$ 20 | 10$^2$ 100 |
|        | 2   | 0.5                             | 1.1                      |             | 11.6 J98  | 1 x 10$^5$ to 3 x 10$^5$ >40 | 1 x 10$^5$ 10 |        |        |       |
| N166   | 1   | 0.3                             | 0.6                      |             | 10.5 G02  | 5 x 10$^5$ to 2 x 10$^5$ 25-150 | 10$^4$ 20 | 10$^2$ to 10$^3$ 30-60 |        |       |
|        | 3   | 0.3                             | 0.6                      |             | 12.6 G02  | 3 x 10$^3$ to 2 x 10$^3$ >30 | 10$^4$ 20 | 10$^2$ to 10$^3$ 30-60 |        |       |
|        | 4   | 0.4                             | 0.7                      |             | 8.5 J98   | 1 x 10$^5$ to 6 x 10$^3$ 20-60 | 1 x 10$^5$ 10 |        |        |       |
| N206   | 1   | 0.5                             | 0.8                      |             | 14.1 This work | 5 x 10$^2$ to 3 x 10$^3$ >35 | 10$^4$ 20 | 10$^2$ to 10$^3$ 30-60 |        |       |
|        | 2   | 0.4                             | 0.5                      |             | 9.8 This work | 6 x 10$^2$ to 2 x 10$^3$ 20-80 | 10$^4$ 20 | 10$^2$ to 10$^3$ 30-60 |        |       |
| N206D  | 1   | 0.3                             | 0.5                      |             | 4.8 This work | 1 x 10$^3$ to 3 x 10$^3$ 10-20 | 10$^4$ 20 | 10$^2$ to 10$^3$ 30-60 |        |       |
| GMC 225| 1   | 0.2                             | 0.4                      |             | 6.6 This work | 5 x 10$^2$ to 2 x 10$^3$ 15-20 | 10$^4$ 20 | 10$^2$ to 10$^3$ 30-60 |        |       |
|        | 2   | 0.3                             | 0.4                      |             | 6.7 This work | 7 x 10$^2$ to 2 x 10$^3$ 10-40 |        |        |        |       |

**Notes.**—Cols. (7) and (8): Results of LVG analysis. Cols. (9)–(20): Results of previous studies, including both LVG and mean escape probability analyses.

**References.**—(J98) Johansson et al. 1998; (G02) Garay et al. 2002; (H99) Heikkilä et al. 1999; (B05 SC) “Single-component fit” in Bolatto et al. 2005; (B05 CDC, B05 HTC) “Cold Dense Component” and “Hot Tenuous Component,” respectively, of the “Dual-component fit” in Bolatto et al. 2005; (K06) Kim 2006.
generally correlated with the star formation activity of GMCs and can perhaps be interpreted in terms of evolutionary effects.

Our interpretation is that differences of clump density and temperature represent an evolutionary sequence of GMCs in terms of density increase leading to star formation; type I/II GMCs are at a young phase of star formation where density has not yet reached high enough values to cause active massive star formation, and type III GMCs represent the later phase where the average density is higher, including both high- and low-density subtypes. The high-density clumps in type III GMCs show high $R_{3-2/1-0,\text{clump}}$ of 1.0–1.5 and are associated with strong H$_\alpha$ flux, while the low-density clumps in type III GMCs show low $R_{3-2/1-0,\text{clump}}$ of 0.5–1.0 with weak H$_\alpha$ flux.

We suggest two alternative ideas to explain the density difference of the clumps in type III GMCs; one is that density is being enhanced by shock compression driven by H II regions, and the other is that gravitational condensation of each clump plays a role in the density increase. The former may be difficult because the shock front may occupy a small volume that is likely missed with the present 5 pc beam. It seems thus favorable that the latter scenario is working mainly to enhance density.

The present study, which resolved the smaller clumps in GMCs at 5–10 pc scales, indicates that the clumps may have physical properties affected by local properties such as the H$_\alpha$ distribution. It should be interesting to investigate the variations among these internal clumps and their relation to star formation.

5.3. FUV Heating of the Molecular Gas in the LMC

The present findings that the $R_{3-2/1-0,\text{clump}}$ is well correlated with H$_\alpha$ flux suggest that the heating of molecular gas by far-ultraviolet (FUV) photons may be effective in the LMC where the dust opacity is lower and the FUV intensity is higher than in the Milky Way. The molecular gas in the Milky Way is mainly heated by cosmic-ray protons of $\sim$100 MeV as discussed by a number of authors, although the surface layers of molecular clouds with small visual extinctions at $A_V$ around a few magnitudes or less may be dominated by the FUV heating (e.g., Kaufman et al. 1999). Some authors have made detailed calculations of gas heating and cooling under the effects of FUV radiation fields (Kaufman et al. 1999). We try to present a picture that can be applied to the present results below.

First, the gas temperature is determined through the balance between the cooling and heating. According to Table 4 in Goldsmith & Langer (1978) the total cooling rate is $6.8 \times 10^{-27} T^{2.22} \text{ergs cm}^{-3} \text{s}^{-1}$ for $X$(CO)/(d$V$/d$R$) = $4 \times 10^{-5}$ and $n$(H$_2$) = $3 \times 10^{3}$ cm$^{-3}$. In the 30 Dor region, since $X$(CO)/(d$V$/d$R$) = $3 \times 10^{-6}$/0.8 = 3.75 $\times 10^{-6}$ and this value is 10 times lower than the value used in Goldsmith & Langer (1978), $n$(H$_2$) = $10^8$ cm$^{-3}$ can be read 10$^3$ cm$^{-3}$, then the cooling rate is estimated as 1.7 $\times 10^{-22}$ ergs cm$^{-3} \text{s}^{-1}$ for $T = 100$ K. This value is a factor 2–3 smaller than that of Galactic clouds with $n$(H$_2$) = $10^4$ cm$^{-3}$ and $T = 50$ K.

We assume that the heating by cosmic-ray electrons is not important in the LMC. This assumption is not directly confirmed, but it is consistent with the low nonthermal fraction of the LMC’s radio continuum emission (e.g., Hughes et al. 2006) and studies that suggest that a significant fraction of cosmic-ray electrons are able to escape from low-luminosity galaxies (e.g., Bell 2003; Skillman & Klein 1988).

The FUV flux ($G_0$) is estimated as 3500 for 30 Doradus (Bolatto et al. 1999; Poglitsch et al. 1995; Werner et al. 1978; Israel & Koornneef 1979) and 300 for N159 (Bolatto et al. 1999; Israel et al. 1996; Israel & Koornneef 1979). In Orion, it is estimated as 25 (Bolatto et al. 1999; Stacey et al. 1993). The FUV flux in the LMC is larger than that in the Milky Way.

Photodissociation region (PDR) models are calculated by Kaufman et al. (1999) that incorporate the chemical and physical processes that form and destruct atoms or molecules, as well as ionization effects. Figure 1 of Kaufman et al. (1999) shows the kinetic temperature for a molecular gas layer with density of $n$(cm$^{-3}$) under FUV flux of $G_0$ at the surface. PDR surface temperatures are estimated as listed in Table 7. These indicate that temperature becomes as high as 100–300 K on the PDR surface under the conditions of the clumps in type III GMCs in the LMC. These temperatures are basically consistent with the temperatures of the warm clumps in the present sample.

![Fig. 20.—Contour plots of LVG analysis of three clumps: (a) 30 Dor No. 1, (b) N206 No. 1, and (c) GMC 225 No. 1. The vertical axis is kinetic temperature $T_{\text{kin}}$, and the horizontal axis is molecular hydrogen density $n$(H$_2$). Solid lines indicate $R_{3-2/1-0,\text{clump}}$, and dashed lines indicate $R_{12/11}$. Hatched areas are the regions in which these two ratios overlap within intensity calibration errors of 20% and uncertainty due to a possible variation of $^{13}$CO/$^{12}$CO abundance ratio from 20 to 30.](image1)

![Fig. 21.—Plot of LVG results. The vertical axis is kinetic temperature, $T_{\text{kin}}$, and the horizontal axis is molecular hydrogen density $n$(H$_2$). See the electronic edition of the Supplement for a color version of this figure.](image2)
Generally speaking, at a scale of ~10 pc, $T_{\text{kin}} \sim 100$ K seems to be higher than the kinetic temperatures typical in Milky Way GMCs, where the Milky Way values are usually derived from the $^{12}\text{CO}(J = 1-0)$ emission only (e.g., $\eta$ Car $T_{\text{kin}} \sim 50$ K by Yonekura et al. 2005). This suggests that the heating of molecular clouds may be stronger in the LMC than in the Milky Way and the molecular temperature may be higher. If this is correct, the lower metallicity, resulting in lower extinction, is the basic cause for the higher temperature in addition to the stronger FUV field in the LMC. We note in the end that this higher temperature in the molecular gas possibly leads to an increase of the Jeans mass of molecular clumps, which may favor the formation of rich superclusters in the LMC. This is consistent with the higher mass of the molecular clumps, which may represent precursors of the clusters.

The present work has undertaken to sample six GMCs (seven regions) to have a uniform determination of the density and temperature in the LMC. The number of GMCs is still limited to 6 among ~300 detected with NANTEN. We should make more efforts to collect appropriate data sets in the submillimeter wavelengths to improve our understanding of the cloud properties.

NANTEN2, ASTE, and others will certainly be powerful in achieving this goal.

6. SUMMARY

We summarize the results as follows.

1. We have used the ASTE 10 m telescope to obtain the distribution of $^{12}\text{CO}(J = 3-2)$ emission at 345 GHz toward six GMCs (seven regions) in the LMC. We have identified 32 clumps in these GMCs at ~5 pc resolution. The radius, line width, and virial mass are estimated as 1.1–12.4 pc (7 pc), 4.0–12.8 km s$^{-1}$ (7 km s$^{-1}$), and 4.6×10$^3$ to 2.2×10$^5$ $M_\odot$ (6×10$^4$ $M_\odot$), respectively, with the average values in the parenthesis.

2. We have compared the present results with LVG radiative line transfer calculations in order to obtain the density and temperature estimated for the 13 clumps using $R_{3-2}/R_{1-0}$,clump and $R_{12}/R_{13}$ at 45° resolution. The clumps are distributed from cool (~10–30 K) to warm (more than ~30–200 K) and from less dense [$n(H_2) \sim 10^3$ cm$^{-3}$] to dense [$n(H_2) \sim 10^{3.5}$–10$^5$ cm$^{-3}$].

3. The $H\alpha$ flux toward these clumps is well correlated with the $^{12}\text{CO}(J = 3-2)/^{13}\text{CO}(J = 1-0)$ ratio, $R_{3-2}/R_{1-0}$,clump, and clumps with $H\alpha$ fluxes greater than 10$^{-11}$ erg s$^{-1}$ cm$^{-2}$ have large $R_{3-2}/R_{1-0}$,clump of ~1.5. The $^{12}\text{CO}(J = 1-0)$ data were taken with the SEST 15 m and Mopra 22 m telescopes.

4. The typical mass of the molecular clumps ranges from 5×10$^3$ to 2×10$^5$ $M_\odot$ with radii of 1–12 pc. Of all of our objects, N159 No. 1 or W shows the strongest concentration of mass of ~7×10$^4$ $M_\odot$ within a radius of ~5 pc. We suggest that these are good candidates for the precursors of rich superclusters like R136 in 30 Dor.

![Fig. 22.—Histogram of clump-averaged H$\alpha$ flux. Background level is nearly 10$^{-12}$ ergs s$^{-1}$ cm$^{-2}$.

![Fig. 23.—Plots of $R_{3-2}/R_{1-0}$,clump as a function of clump-averaged H$\alpha$ flux by (a) region and (b) GMC type. [See the electronic edition of the Supplement for a color version of this figure.]](image-url)
5. We suggest that differences of clump properties represent an evolutionary sequence of GMCs in terms of density increase leading to star formation. Type I/II GMCs are at a young phase of star formation where density has not yet reached high enough values to cause active massive star formation, and type III GMCs represent the later phase where the average density is higher, including both high- and low-density subtypes.

6. The high kinetic temperature correlated with Hα flux suggests that FUV heating is dominant in the molecular gas of the LMC. The low fraction of nonthermal radio continuum emission and calculations of PDR models support this suggestion. Furthermore, the high temperature in the molecular gas possibly leads to an increase of the Jeans mass of molecular clumps, which may favor the formation of rich superclusters.

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APPENDIX A

COMPLETE LVG RESULTS OF ALL CLUMPS

Figures 25–37 show the complete LVG results described in §4.2. We present all cases: X(CO) of (a) $1 \times 10^{-6}$, (b) $3 \times 10^{-6}$, and (c) $1 \times 10^{-5}$ for 13 clumps.

| Region    | n (cm$^{-3}$) | $G_0$ (erg cm$^{-2}$ s$^{-1}$ K$^{-1}$) | $T_{\text{kin}}$ (K) | References |
|-----------|---------------|----------------------------------------|-----------------------|------------|
| 30 Dor................. | $10^4$         | 3500                                   | 300                   | 1, 2, 3, 4 |
| N159............... | $10^4$         | 300                                    | 100                   | 1, 4, 5    |

Notes.—Col. (1): Regions. Col. (2): Gas density. Col. (3): FUV flux in units of local interstellar value; $6 \times 10^{-3}$ erg cm$^{-2}$ s$^{-1}$. Col. (4): Derived PDR surface temperature of the atomic gas. Col. (5): References of FUV flux.

* Estimation is done by using Fig. 1 of Kaufman et al. 1999.

References.—(1) Bolatto et al. 1999; (2) Poglitsch et al. 1995; (3) Werner et al. 1978; (4) Israel & Koornneef 1979; (5) Israel et al. 1996.
Fig. 26.—Same as Fig. 25, but for 30 Dor No. 4.

Fig. 27.—Same as Fig. 25, but for N159 No. 1.

Fig. 28.—Same as Fig. 25, but for N159 No. 2.
Fig. 29.—Same as Fig. 25, but for N159 No. 4.

Fig. 30.—Same as Fig. 25, but for N166 No. 1.

Fig. 31.—Same as Fig. 25, but for N166 No. 3.
Fig. 32.—Same as Fig. 25, but for N166 No. 4.

Fig. 33.—Same as Fig. 25, but for N206 No. 1.

Fig. 34.—Same as Fig. 25, but for N206 No. 2.
Fig. 35.—Same as Fig. 25, but for N206D No. 1.

Fig. 36.—Same as Fig. 25, but for GMC 225 No. 1.

Fig. 37.—Same as Fig. 25, but for GMC 225 No. 3.
Fig. 38.—Plot of relation between integrated Hα flux and FITS value. The solid line represents the least-squares fit.

Fig. 39.—Plots of physical properties as a function of $R_{3}$: (a) $n$(H$_2$) by region. (b) $n$(H$_2$) by GMC type. (c) $T_{\text{kin}}$ by region. (d) $T_{\text{kin}}$ by GMC type. [See the electronic edition of the Supplement for a color version of this figure.]
We here describe the method of scaling data values in the FITS cube (Hα image in Kim et al. [1999], hereafter “Kim’s FITS”). The data values in Kim’s FITS are not flux scale, and the calibration is needed for quantitative comparison with CO clouds and $R_{3-2}/Y_0$. The procedure is as follows. (1) Sum up the data values of Kim’s FITS inside apertures, which are listed in Kennicutt & Hodge (1986) for each listed H ii region. (2) Plot cataloged values of Hα flux in Kennicutt & Hodge (1986) as a function of summed values derived in step 1. They are well fitted by a power function of $y = 5.16 \times 10^{-15} \times 0.9$ (c.c. = 0.94; Fig. 38). (3) Convert data values of Kim’s FITS to Hα flux scale (ergs s$^{-1}$ cm$^{-2}$) using the function derived above.

**APPENDIX C**

**LVG RESULTS IN THE OTHER PLANES**

C1. PHYSICAL PROPERTIES: $R_{3-2}/Y_0$ clump (Fig. 39)

The density plots (Figs. 39a and 39b) show that higher $R_{3-2}/Y_0$ clump ($>1.0$) correspond to higher densities of $10^3$–$10^5$ cm$^{-3}$, while lower $R_{3-2}/Y_0$ clump ($<1.0$) correspond to lower densities of around $10^4$ cm$^{-3}$. The temperature plots (Figs. 39c and 39d) show that higher $R_{3-2}/Y_0$ clump ($>0.5$) correspond to higher temperatures of $>30$ K, while lower $R_{3-2}/Y_0$ clump ($<0.5$) correspond to lower temperatures of $<30$ K.

Then, roughly speaking, we can say that clumps with $R_{3-2}/Y_0$ clump lower than 0.5 have lower densities of around $10^3$ cm$^{-3}$ and lower temperatures of $<30$ K, clumps with $R_{3-2}/Y_0$ clump of 0.5–1.0 have lower density around $10^5$ cm$^{-3}$ and higher temperatures of $>30$ K, and clumps with $R_{3-2}/Y_0$ clump higher than 1.0 have higher densities of $10^3$–$10^5$ cm$^{-3}$ and higher temperatures of $>30$ K, although ratios, densities, and temperatures are with large error bars.

Of course, there are great benefits to using $R_{12}/I_3$ in LVG analyses. We could not have obtained the above results with only $R_{3-2}/Y_0$, as mentioned in § 4.

**APPENDIX B**

**Hα FLUX**

Fig. 40.—Same as Fig. 39, but as a function of $R_{12}/I_3$. [See the electronic edition of the Supplement for a color version of this figure.]

Fig. 41.—Plots of $R_{12}/I_3$ as a function of clump-averaged Hα flux (a) by region and (b) by GMC type. [See the electronic edition of the Supplement for a color version of this figure.]
C2. PHYSICAL PROPERTIES: $R_{12/13}$ (FIG. 40)

The density (Figs. 40a and 40b) does not show a significant correlation with $R_{12/13}$. The temperature (Figs. 40c and 40d) shows a good correlation with $R_{12/13}$; that is, higher ratios indicate higher temperatures. Usually, $R_{12/13}$ correspond to density, but in this case, due to the LVG analysis using both $R_{32/12}$ and $R_{12/13}$, larger $R_{12/13}$ indicate lower density and lower density tends to higher temperature.

C3. $R_{12/13}$-H$\alpha$ FLUX (FIG. 41)

There is no significant relation between $R_{12/13}$ and H$\alpha$ flux, in contrast to the case for the $R_{32/12}$-H$\alpha$ ratio.

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