\textbf{$^{13}$CO($J = 1 - 0$) On-the-fly Mapping of the Giant H II Region NGC 604: Variation in Molecular Gas Density and Temperature due to Sequential Star Formation}

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\textbf{Abstract}

We present $^{13}$CO($J = 1 - 0$) line emission observations with the Nobeyama 45-m telescope toward the giant H II region NGC 604 in the spiral galaxy M 33. We detected $^{13}$CO($J = 1 - 0$) line emission in 3 major giant molecular clouds (GMCs) labeled as GMC-A, B, and C beginning at the north. We derived two line intensity ratios, $^{13}$CO($J = 1 - 0$)/$^{12}$CO($J = 1 - 0$), $R_{13/12}$, and $^{12}$CO($J = 3 - 2$)/$^{12}$CO($J = 1 - 0$), $R_{31}$, for each GMC at an angular resolution of 25$''$ (100 pc). Averaged values of $R_{13/12}$ and $R_{31}$ are 0.06 and 0.31 within the whole GMC-A, 0.11 and 0.67 within the whole GMC-B, and 0.05 and 0.36 within the whole GMC-C, respectively. In addition, we obtained $R_{13/12} = 0.09 \pm 0.02$ and $R_{31} = 0.76 \pm 0.06$ at the $^{12}$CO($J = 1 - 0$) peak position of the GMC-B. Under the Large Velocity Gradient approximation, we determined gas density of $2.8 \times 10^3$ cm$^{-3}$ and kinetic temperature of $33^{+9}_{-5}$ K at the $^{12}$CO($J = 1 - 0$) peak position of the GMC-B. Moreover, we determined $2.5 \times 10^3$ cm$^{-3}$ and $25 \pm 2$ K as averaged values within the whole GMC-B. We concluded that dense molecular gas is formed everywhere in the GMC-B because derived gas density not only at the peak position of the GMC but also averaged over the whole GMC exceeds $10^3$ cm$^{-3}$. On the other hand, kinetic temperature averaged over the whole GMC-B, 25 K, is significantly lower than that at the peak position, 33 K. This is because H II regions are lopsided to the northern part of the GMC-B, thus OB stars can heat only the
northern part, including the $^{12}\text{CO}(J = 1 - 0)$ peak position, of this GMC.

**Key words:** galaxies: ISM—galaxies: individual (M 33) — ISM: individual objects (NGC 604)

1. **Introduction**

The molecular interstellar medium (ISM) is one of the crucial components in galaxies. In particular, warm and/or dense molecular gas play an important key role on star formation because stars are formed from the *dense* cores of molecular clouds and UV radiation from OB stars in massive star forming regions can easily heat neighboring molecular clouds locally (e.g., Minamidani et al. 2011). Therefore, it is essential to investigate basic physical state, density and temperature, of molecular ISM for understanding of the evolutions of molecular clouds and star formation.

In our galaxy, a large fraction of molecular ISM is in a form of giant molecular clouds (GMCs; Scoville & Sanders 1987, Solomon et al. 1985), which are known to be major sites of massive star formation. Typical sizes of GMCs are a few 10 pc – 100 pc. For this spatial scale, a lot of observational studies of molecular gas, star formation, and their relationships have been carried out toward local group galaxies. For example, Kawamura et al. (2009) made a positional comparison of GMCs with classical H$\text{II}$ regions and clusters in Large Magellanic Cloud (LMC) at a $\sim 40$ pc resolution. They classified GMCs into three types in terms of star formation activities, i.e., type I GMCs with no signs of massive star formation, type II GMCs associated with only small H$\text{II}$ regions, and type III GMCs associated with both H$\text{II}$ regions and young stellar clusters. The authors suggest these types reflect evolutionary stages of GMCs.

In addition, Minamidani et al. (2011) derived intensity ratios of $^{12}\text{CO}(J = 3 - 2)/^{13}\text{CO}(J = 3 - 2)$ and $^{18}\text{CO}(J = 3 - 2)/^{13}\text{CO}(J = 1 - 0)$, and determined density and kinetic temperature of molecular gas including all three types of GMCs in LMC by the application of the Large Velocity Gradient (LVG) analysis. The authors found that the type I GMC with no signs of massive star formation shows its gas density of $\sim 1 \times 10^3$ cm$^{-3}$ and kinetic temperature of 25 K, suggesting less dense and cool molecular gas. On the other hand, they found that type II and III GMCs, which are associated with H$\text{II}$ regions show their gas density of $3 - 5 \times 10^3$ cm$^{-3}$ and kinetic temperature exceeding 30 K, suggesting dense and warm molecular gas.

In local group galaxies, one of the nearest spiral galaxy, M 33 ($D = 840$ kpc; Freedman et al. 1991), is also a very important target to perform observational studies of molecular gas and star formation. Its proximity and the relatively small inclination ($i = 51$ degree; Deul & van der Hulst 1987) of M 33 enable us to resolve individual GMCs even with existing large aperture single dishes. In addition, contrary to LMC, M 33 is able to be observed with various telescopes existing in the Northern Hemisphere. Thus, many observational studies of molecular ISM in
M 33 have been performed. For example, whole disk surveys of molecular gas in $^{12}$CO($J = 1 - 0$) line emission have been carried out with the BIMA interferometer (Engargiola et al. 2003) and the FCRAO 14-m telescope (Heyer et al. 2004). In addition, Rosolowsky et al. (2007) combined them with observations using the 45-m telescope at the Nobeyama Radio Observatory (NRO) toward a part of the disk. A partial mapping of $^{12}$CO($J = 2 - 1$) line emission has also been made with the IRAM 30-m telescope (Gratier et al. 2010). Recently, the NRO M 33 All disk survey of Giant molecular Clouds (NRO MAGiC) project using the NRO 45-m telescope is ongoing. Tosaki et al. (2011) report initial results of the NRO MAGiC, presenting a high-quality and wide-field ($30' \times 30'$ or 7.3 kpc $\times$ 7.3 kpc) image in $^{12}$CO($J = 1 - 0$) line emission at a resolution of 19''3 (80 pc). Using the data, Onodera et al. (2010) found that a tight correlation between the surface densities of molecular gas and those of star formation rates seen in a few 100 pc $\sim$ a few kpc scales in galaxies, known as Kennicutt-Schmidt law (Kennicutt 1998), seems to be broken down in a $\sim$ 100 pc scale or smaller in M 33.

Detailed observations of the giant H II region NGC 604 in M 33 are also reported. Tosaki et al. (2007a) examined $^{12}$CO($J = 3 - 2$)/$^{12}$CO($J = 1 - 0$) intensity ratio, hereafter $R_{31}$, and discovered high intensity ratio gas with an arc-like distribution similar to H$\alpha$ emission, suggesting that the sequential star formation is ongoing. Miura et al. (2010) observed $^{12}$CO($J = 1 - 0$) line, HCN($J = 1 - 0$) line, and 89 GHz continuum emission using the Nobeyama Millimeter Array (NMA). They proposed a scenario of sequential star formation in which the massive star formation propagates through the expansion of the H$\alpha$ emission nebula excited by the central OB star cluster. These observational studies clearly suggest the importance of multi-line/transition observations in mm/sub-mm waveband.

In this paper, we present $^{13}$CO($J = 1 - 0$) images of NGC 604 obtained with the NRO 45-m telescope. $^{13}$CO($J = 1 - 0$) line emission is known to as a tracer of dense molecular gas ($n_{H_2} \sim 10^{3-4}$ cm$^{-3}$). Since the existing $^{12}$CO($J = 1 - 0$) data can trace the total amount of molecular gas, the intensity ratio of $^{13}$CO($J = 1 - 0$)/$^{12}$CO($J = 1 - 0$), hereafter $R_{13/12}$, can be used as an indicator of gas density with a low or moderate temperature. In addition, usage of $^{12}$CO($J = 3 - 2$) data obtained by Tosaki et al. (2007a) enables us to obtain another line intensity ratio, $R_{31}$, which is also an indicator of gas density. The combination of these two line ratios allows us to determine gas density and kinetic temperature of molecular gas simultaneously under the LVG approximation (e.g., Minamidani et al. 2008). Then, we will be able to compare physical properties of molecular gas, such as density and temperature, to the star formation activity in NGC 604.

The goals of this paper are: (1) to reveal the distribution of $^{13}$CO($J = 1 - 0$) line emission in NGC 604, (2) to derive $R_{13/12}$ and $R_{31}$, and determine the density and kinetic temperature of molecular gas under the LVG approximation, and (3) to investigate how these physical state of molecular gas, such as gas density and temperature, connect with the sequential star formation proposed by Tosaki et al. (2007a).
2. Observations and Data

\(^{13}\text{CO}(J = 1 - 0)\) line emission observations of NGC 604 were performed using the NRO 45-m telescope from 2009 May 9 – 20, employing on-the-fly (OTF) mapping mode. The total time for the observations was 21 hours. The size of the \(^{13}\text{CO}(J = 1 - 0)\) map is about \(2' \times 2'\) \((480 \times 480 \text{ pc})\), and the mapped area is indicated in figure 1.

We used a new waveguide-type dual-polarization sideband-separating 100-GHz band SIS receiver, T100 (Nakajima et al. 2008). The half-power beam width of the telescope for two polarizations was \(15''\pm0.2\) and \(15''.4 \pm 0''.2\), the image rejection ratio was 13 dB and 30 dB, and the main beam efficiency of the 45-m telescope at 110 GHz was 0.40 and 0.44, respectively. The system noise temperature was typically 200 – 250 K (in single sideband) during the observing run. We used digital spectrometers with a band width of 512 MHz and 1024 channels, corresponding to a velocity coverage of 1393 km s\(^{-1}\).

OTF mapping was performed along two different directions (i.e., scans along the R.A. and decl. directions), and these two data sets were co-added by the Basket-weave method (Emerson & Graeve 1988) in order to remove any effects of scanning noise. At the beginning of each OTF scan, an off-source position, which was \(\pm 30'\) offset in the R.A. direction from the map center taken at \(\alpha = 1^h 34^m 33^s 20, \delta = 30^\circ 47' 06'' 00\) (J2000), was observed to subtract sky emission. The absolute pointing accuracy was checked every hour with an SiO maser source, IRC +30021, using a 43 GHz SIS receiver (S40). It was better than \(6''\) (peak-to-peak) throughout the observations.

The data reduction was made using the software package NOSTAR, which comprises tools for OTF data analysis, developed by NAOJ (Sawada et al. 2008). The raw data were regridded to \(7''.5\) per pixel, giving an effective spatial resolution of approximately \(20''\) (or 80 pc). Linear baselines were subtracted from the spectra. We binned the adjacent channels to a velocity resolution of 2.5 km s\(^{-1}\) for the \(^{13}\text{CO}(J = 1 - 0)\) spectra. Going through these procedures, a 3D data cube was created. The resultant r.m.s. noise level (1 \(\sigma\)) was typically in the range of 25 to 30 mK in the \(T_{MB}\) scale.

In order to derive two line ratios, \(R_{13/12}\) and \(R_{31}\), we used \(^{12}\text{CO}(J = 1 - 0)\) data obtained with the NRO 45-m telescope (Miura et al. 2010) and \(^{12}\text{CO}(J = 3 - 2)\) data obtained with the Atacama Submillimeter Telescope Experiment (ASTE) 10-m (Tosaki et al. 2007a). In order to make the comparison among each CO line easier, both \(^{12}\text{CO}(J = 1 - 0)\) and \(^{12}\text{CO}(J = 3 - 2)\) data were regridded to match \(^{13}\text{CO}(J = 1 - 0)\) data using the NRAO AIPS task HGEOM. In addition, we have convolved both \(^{12}\text{CO}(J = 1 - 0)\) and \(^{13}\text{CO}(J = 1 - 0)\) data, whose original angular resolution is 20'', to 25'' in order to match the \(^{12}\text{CO}(J = 3 - 2)\) data for further discussion. After the convolution of \(^{13}\text{CO}(J = 1 - 0)\) data cube to 25'', its r.m.s. noise level (1 \(\sigma\)) decreased to 16 mK in the \(T_{MB}\) scale. Observation parameters in each CO line are listed in table 1.
3. Results

3.1. Distribution of $^{13}$CO($J = 1 - 0$) intensity and its comparison with other emission

We calculated velocity-integrated intensities of $^{13}$CO($J = 1 - 0$) and $^{12}$CO($J = 1 - 0$) line emission of NGC 604 as shown in figure 2. This map suggests that two GMCs are overlapping in line-of-sight in the south-eastern region. Thus, we examined spectra of both $^{13}$CO($J = 1 - 0$) and $^{12}$CO($J = 1 - 0$) line in figure 3, and found the existence of two velocity components. One is within a velocity range of $-260$ to $-230$ km s$^{-1}$, which is referred to as “blue” component in this paper, and the other is $-230$ to $-210$ km s$^{-1}$ referred to as “red”. Therefore, we recalculated velocity-integrated intensities of each CO line emission to separate red and blue components. Figure 4 shows a new $^{13}$CO($J = 1 - 0$) integrated intensity map, separating these two velocity components.

Figure 5 shows comparisons among maps of integrated-intensity in $^{13}$CO($J = 1 - 0$), $^{12}$CO($J = 1 - 0$), and $^{12}$CO($J = 3 - 2$) line emission, respectively. In addition, we compared the distribution of $^{13}$CO($J = 1 - 0$) line emission to that of H$\alpha$ luminosity (Hoopes & Walterbos 2000). We finally found 3 GMCs in $^{12}$CO($J = 1 - 0$) intensity maps, and labeled these GMCs as GMC-A, B, and C beginning at the north as shown in figure 5. The GMC-A and B correspond to blue components, and the GMC-C corresponds to a red component. Every GMCs are already identified by Rosolowsky et al. (2007); the GMC-A, B, and C correspond to the GMC number 122, 124, and 126 in Rosolowsky et al. (2007) sample, respectively. Each GMC has counterparts in $^{13}$CO($J = 1 - 0$) and $^{12}$CO($J = 3 - 2$) line emission. However, massive star forming regions traced by H$\alpha$ emission only exist in the northern part of the central $^{13}$CO($J = 1 - 0$) emitting region. In addition, the distribution of H$\alpha$ emission is very similar to that of 8.4 GHz radio continuum (Churchwell & Goss 1999), which also trace massive star forming regions. This means that massive star formation is ongoing only in the northern part of the GMC-B.

3.2. Derivation of $R_{13/12}$ and $R_{31}$ in each GMC

In order to compare physical properties among these 3 GMCs, we derive two line intensity ratios, $R_{13/12}$ and $R_{31}$. The absolute errors of the $^{12}$CO($J = 1 - 0$), $^{13}$CO($J = 1 - 0$), and $^{12}$CO($J = 3 - 2$) intensities caused by calibration uncertainties were estimated to be 15%, respectively. Thus, the absolute error of each line ratio is estimated to be 30%. For the GMC-B, we derive $R_{13/12}$ and $R_{31}$ in two different ways. One is at the $^{12}$CO($J = 1 - 0$) peak position ($1^h34^m33.42$, $30^\circ46'51.77''$), which is $\sim 22''$ offset in the south-east direction from the central star cluster, and the other is an averaged value within the whole GMC. Note that we cannot make the “map” of $R_{13/12}$ such as that of $R_{31}$ reported by Tosaki et al. (2007a). This is because the signal-to-noise ratio of $^{13}$CO($J = 1 - 0$) data is insufficient to make the line-ratio map.

We obtain an averaged line ratio within the whole GMC according to the following procedure. First, we define the “border” of the GMC using the data of $^{12}$CO($J = 1 - 0$)
integrated intensity. For a GMC, we treat a pixel whose value is more than the half of the peak value in the GMC as the “GMC pixel”. This “GMC pixel” is applied to each CO lines in common. Then, we sum up the values of all the “GMC pixel” in each CO line, and obtain the total pixel values of $^{13}\text{CO} (J = 1 - 0)$, $^{12}\text{CO} (J = 1 - 0)$, and $^{12}\text{CO} (J = 3 - 2)$ line intensity for the GMC, respectively. Finally, we calculate $\frac{R_{13}}{R_{12}}$ and $\frac{R_{31}}{R_{32}}$ according to these total pixel values. Thus, we obtained $\frac{R_{13}}{R_{12}} = 0.11 \pm 0.01$ and $\frac{R_{31}}{R_{32}} = 0.67 \pm 0.02$ as averaged values within the whole GMC-B, and obtained $\frac{R_{13}}{R_{12}} = 0.09 \pm 0.02$ and $\frac{R_{31}}{R_{32}} = 0.76 \pm 0.06$ at the peak position of the GMC-B, respectively.

On the other hand, for the GMC-A and C, their sizes (70 – 80 pc) are smaller than that of the GMC-B (> 100 pc). In addition, peak positions of each CO line emission are offset (5" – 10") each other. Thus, we derive only averaged values of $\frac{R_{13}}{R_{12}}$ and $\frac{R_{31}}{R_{32}}$ within each whole GMC as we do for the GMC-B. We obtained $\frac{R_{13}}{R_{12}} = 0.06 \pm 0.01$ and $\frac{R_{31}}{R_{32}} = 0.31 \pm 0.04$ for the GMC-A, and obtained $\frac{R_{13}}{R_{12}} = 0.05 \pm 0.01$ and $\frac{R_{31}}{R_{32}} = 0.36 \pm 0.03$ for the GMC-C, respectively. Note that since the $^{13}\text{CO} (J = 1 - 0)$ emitting region associated with the GMC-C seems to be distributed beyond the mapped area, the derived $\frac{R_{13}}{R_{12}}$ value of the GMC-C contain additional errors compared to other GMCs. We found significant differences in derived line intensity ratios between the GMC-B and other two GMCs; both $\frac{R_{13}}{R_{12}}$ and $\frac{R_{31}}{R_{32}}$ of the GMC-B are larger than those of the GMC-A and C. This suggests differences in physical properties of ISM among these GMCs, which will be discussed further in the following section.

We compare observed $\frac{R_{13}}{R_{12}}$ values in NGC 604 to those obtained by Wilson et al. (1997), who reported a robust LVG analysis for several regions in M 33 including NGC 604. For the peak position of GMC-B, which is labeled as NGC 604-2 in Wilson et al. (1997), the authors obtained $\frac{R_{13}}{R_{12}} = 0.07 – 0.10$. This seems consistent with our $\frac{R_{13}}{R_{12}}$, 0.09 – 0.11. In addition, we compare our $\frac{R_{13}}{R_{12}}$ values in NGC 604 to those in our galaxy and other local group galaxies. In the Galactic disk, the averaged $\frac{R_{13}}{R_{12}}$ value is 0.15 – 0.18 (Solomon et al. 1979, Polk et al. 1988). In some regions of LMC, the reported $\frac{R_{13}}{R_{12}}$ value is in the range of 0.05 to 0.21 (Johansson et al. 1998, Garay et al. 2002, Minamidani et al. 2008). Tosaki et al. (2007b) found $\frac{R_{13}}{R_{12}} = 0.16$ at the center of a Giant Molecular Association (GMA) of M 31, and found a possible sign of a radial gradient on $\frac{R_{13}}{R_{12}}$ from the center to the outer edge of the GMA, where the observed $\frac{R_{13}}{R_{12}}$ value is 0.11. Therefore, $\frac{R_{13}}{R_{12}}$ for the GMC-B, 0.09 – 0.11, seems to be typical values or a little lower, whereas $\frac{R_{13}}{R_{12}}$ of the GMC-A and C, 0.05 – 0.06, seems to be significantly lower values compared to that in our galaxy and in other local group galaxies.

4. Discussion

As described in the previous section, it seems that physical properties of molecular ISM are different among these 3 GMCs considering the differences in $\frac{R_{13}}{R_{12}}$ and $\frac{R_{31}}{R_{32}}$ values. In this section, we show the further analysis of ISM properties for each GMC. In particular, we derive
density and kinetic temperature of molecular gas using $R_{13/12}$ and $R_{31}$. Then, we discuss the relationship among gas density, kinetic temperature, star formation activity, and their evolution of molecular clouds comprehensively. However, we cannot accurately obtain $R_{13/12}$ in the GMC-C because $^{13}\text{CO}(J = 1 \rightarrow 0)$ line emission is distributed beyond the mapped area. Therefore, we exclude the GMC-C in further discussion.

4.1. Determination of physical properties from LVG analysis

In order to obtain physical properties of molecular gas, such as its density and kinetic temperature, we employed the LVG approximation (Scoville & Solomon 1974, Goldreich & Kwan 1974). When we perform the LVG calculation, we have to assume some input parameters; the molecular abundances $Z^{(12}\text{CO}) = [^{12}\text{CO}]/[\text{H}_2]$, $[^{13}\text{CO}]/[^{12}\text{CO}]$, and the velocity gradient $dv/dr$. First, we fix the abundance $[^{13}\text{CO}]/[^{12}\text{CO}]$ as 0.02. Then, we determine an appropriate $Z^{(12}\text{CO})$ value for NGC 604 based on earlier studies as follows. Solomon et al. (1979) reported the standard relative molecular abundance as $Z^{(13}\text{CO}) = 1 \times 10^{-6}$ in the galactic disk, which corresponds to $Z^{(12}\text{CO}) = 5 \times 10^{-5}$ under the assumption of $[^{13}\text{CO}]/[^{12}\text{CO}] = 0.02$. However, Minamidani et al. (2008) assumed a smaller value, $Z^{(12}\text{CO}) = 3 \times 10^{-6}$ for LMC. In order to determine the appropriate $Z^{(12}\text{CO})$ value for NGC 604, we consider a difference in the metallicity among these objects; our galaxy, LMC, and NGC 604. Reported metallicity values are 8.9 in solar neighborhood (Shaver et al. 1983), 8.37 in LMC (Dufour et al. 1982), and 8.51 – 8.60 in NGC 604 (Vilchez et al. 1988, Esteban et al. 2009). Since the metallicity in NGC 604 is between that in our galaxy and in LMC, we adopt an intermediate $Z^{(12}\text{CO})$ value, $1 \times 10^{-5}$, for NGC 604. In addition, we assume $dv/dr$ of 1.0 km s$^{-1}$ pc$^{-1}$, because the sizes of molecular clouds detected with the NMA is in the range of 5 to 29 pc (Miura et al. 2010), and typical velocity width in $^{12}\text{CO}(J = 1 \rightarrow 0)$ line is $\sim 20$ km s$^{-1}$. Figure 6 shows results of the LVG calculations for the GMC-A and B. The black line indicates a curve of constant $R_{13/12}$ as functions of gas density and kinetic temperature, and the red line indicates that of constant $R_{31}$. The usage of these two line ratios allows us to determine density, $n_{\text{H}_2}$, and kinetic temperature, $T_K$, of molecular gas at the point where two curves intersect each other.

For the GMC-A, we determined $n_{\text{H}_2} \sim 7.9 \times 10^2$ cm$^{-3}$ and $T_K = 22^{+9}_{-4}$ K as averaged values within the whole GMC. For the GMC-B, we determined $n_{\text{H}_2} \sim 2.5 \times 10^3$ cm$^{-3}$ and $T_K = 25^{+2}_{-2}$ K as averaged values within the whole GMC. In addition, we determined $n_{\text{H}_2} \sim 2.8 \times 10^3$ cm$^{-3}$ and $T_K = 33^{+9}_{-5}$ K at the $^{12}\text{CO}(J = 1 \rightarrow 0)$ peak position of the GMC-B. Generally, molecular gas whose density exceeding a few $\times 10^3$ cm$^{-3}$ is classified into “dense”, and whose kinetic temperature exceeding 30 K is into “warm” (e.g., Minamidani et al. 2008). Therefore, the physical state of molecular gas averaged over the whole GMC-A is “less dense and cool”, that averaged over the whole GMC-B is “dense and cool”, and that at the peak position of the GMC-B is classified into “dense and warm”, respectively. These results suggest dense gas formation is ongoing in the whole GMC-B, while gas temperature is different within the GMC-
B. Note that the obtained physical properties of GMC-B in this study are different from those obtained by Wilson et al. (1997). The authors reported that gas density is $1 - 3 \times 10^3$ cm$^{-3}$, which is consistent well with our results, whereas the reported temperature is $100 - 300$ K, which is significantly higher than our results, $\sim 30$ K. This is because the authors used not $R_{31}$ but $^{12}$CO($J = 3 - 2$)/$^{12}$CO($J = 2 - 1$) for the LVG calculation. $R_{31}$ significantly differs among galaxies even which show similar $^{12}$CO($J = 3 - 2$)/$^{12}$CO($J = 2 - 1$) ratio (e.g., Mauersberger et al. 1999). Therefore, we suggest that the discrepancy in the derived temperature is caused by the usage of different line ratios, $R_{31}$ and $^{12}$CO($J = 3 - 2$)/$^{12}$CO($J = 2 - 1$), for the LVG calculation.

Here, we mention effects on our results of the LVG calculation when we adopt a different $Z(^{12}$CO) value. If we assume a smaller $Z(^{12}$CO) value, $3 \times 10^{-6}$, like LMC, the derived gas density increases by about 2.5 times, and the derived temperature drops $\sim 15$ K. If we assume a larger $Z(^{12}$CO) value, $5 \times 10^{-5}$, like galactic disks, the derived gas density typically decreases to one third, and the derived temperature typically increases by $\sim 15$ K. In addition, we estimate how derived gas density and temperature vary when we adopted a different $[^{13}$CO]/$[^{12}$CO] abundance ratio as studied in Wilson et al. (1997). If we assume a smaller $[^{13}$CO]/$[^{12}$CO] abundance ratio, 0.014, the derived gas density increases by 1.5 – 2 times, and the derived temperatures drop $\sim 10$ K. If we assume a larger $[^{13}$CO]/$[^{12}$CO] abundance ratio, 0.033, the derived gas density typically drops by half, and the derived temperature increases by $\sim 10$ K. However, relative difference in derived gas density between these GMCs is retained even if we adopted different $Z(^{12}$CO) value and $[^{13}$CO]/$[^{12}$CO] ratio. In other words, determined gas density of GMC-B is still higher than that of GMC-A.

We summarize line ratios and derived physical parameters for each GMC in table 2.

4.2. Evolutional stage of star formation for GMC-B

We discuss evolutional stages of molecular gas and star formation in NGC 604 according to the results of the LVG analysis. In particular, we focus on star formation properties in the GMC-B because we can easily compare our results with earlier studies.

Star formation properties in the GMC-B of NGC 604 have been studied in detail by Tosaki et al. (2007a). The authors examined distributions of $R_{31}$ and H$\alpha$ emission. They found an arc-like high $R_{31}$ structure extending southward, and found that the high $R_{31}$ gas arc closely coincides with the shells of the H$\Pi$ regions traced by H$\alpha$ emission. This shell-shaped H$\Pi$ regions are also displayed in figure 5. They regard the high $R_{31}$ gas arc as dense-gas forming region, and finally suggest that dense gas formation progresses via the compression of surrounding molecular gas by the stellar winds and supernovae from young massive stars in H$\Pi$ regions, and as a result, the dense gas and massive star formation propagates southward in NGC 604 (Miura et al. 2010).

According to Fig.3 and Fig.4 of Tosaki et al. (2007a), the high $R_{31}$ region widely spreads
compared to the shell-shaped H II regions. We compare spatial extent of dense gas forming region indicated by high $R_{31} (> 0.7)$ arc and that of H II regions with the integrated-intensity maps of $^{13}$CO($J = 1 - 0$) and $^{12}$CO($J = 1 - 0$) line emission in figure 7. The dense gas forming region (high $R_{31}$ arc) covers most of the GMC-B, whereas H II regions exist only in the northern part of this GMC. This picture is consistent well with our results of the LVG calculation; the fact that derived gas density not only at the peak position of the GMC but also averaged over the whole GMC exceed $10^3$ cm$^{-3}$ suggests that dense molecular gas is formed everywhere in the GMC-B. On the other hand, kinetic temperature averaged over the whole GMC-B, 25 K, is lower than that at the peak position, 33 K. This is because H II regions are lopsided to the northern part of the GMC-B, and then young massive OB stars can heat only the northern part, including the peak position, of this GMC.

In conclusion, this study based on multi-line CO data and the LVG analysis in NGC 604 suggests that dense molecular gas is formed everywhere in the GMC-B, whereas warm molecular gas, whose kinetic temperature exceeds 30 K, exists only in the northern part of the GMC-B. Since H II regions traced by strong Hα emission are confined in the northern part of the GMC-B, we conclude that young massive OB stars in this H II regions play a key role in heating of neighboring molecular gas locally. Our results support the scenario of the sequential star formation proposed by Tosaki et al. (2007a); i.e., we revealed that the southern part of the GMC-B is in the dense-gas forming phase as predicted by this scenario.

5. Summary

We present $^{13}$CO($J = 1 - 0$) line emission observations with the NRO 45-m telescope toward the giant H II region NGC 604 in the nearest face-on spiral galaxy M 33. The size of $^{13}$CO($J = 1 - 0$) map is about $2' \times 2'$ (480 × 480 pc). A summary of this work is as follows.

1. We successfully detected $^{13}$CO($J = 1 - 0$) line emission in NGC 604. We identified 3 major GMCs in $^{12}$CO($J = 1 - 0$) intensity map, and found that each GMC has counterparts in $^{13}$CO($J = 1 - 0$) and $^{12}$CO($J = 3 - 2$) line emission.
2. We derived two line intensity ratios, $R_{13/12}$ and $R_{31}$, for each GMC at an angular resolution of 25$''$ (100 pc). Averaged values of $R_{13/12}$ and $R_{31}$ are 0.06 and 0.31 within the whole GMC-A, 0.11 and 0.67 within the whole GMC-B, and 0.05 and 0.36 within the whole GMC-C, respectively. In addition, we obtained $R_{13/12} = 0.09 \pm 0.02$ and $R_{31} = 0.76 \pm 0.06$ at the $^{12}$CO($J = 1 - 0$) peak position of the GMC-B.
3. Using $R_{13/12}$ and $R_{31}$, we calculated density and kinetic temperature of molecular gas by the application of the LVG approximation for the GMC-A and B. We determined $n_{H_2} \sim 7.9 \times 10^2$ cm$^{-3}$ and $T_K = 22^{+9}_{-4}$ K as averaged values within the GMC-A, suggesting less dense and cool molecular gas. On the other hand, we determined $n_{H_2} \sim 2.5 \times 10^3$ cm$^{-3}$ and $T_K = 25 \pm 2$ K as averaged values within the whole GMC-B, suggesting dense and cool gas. In addition, we determined $n_{H_2} \sim 2.8 \times 10^3$ cm$^{-3}$ and $T_K = 33^{+9}_{-6}$ K at the $^{12}$CO($J = 1 - 0$) peak position of the GMC-B.
peak position of the GMC-B, suggesting dense and warm gas.

4. We concluded that dense molecular gas is formed everywhere in the GMC-B because derived gas density not only at the peak position of the GMC but also averaged over the whole GMC exceeds $10^3$ cm$^{-3}$, On the other hand, kinetic temperature averaged over the whole GMC-B, 25 K, is lower than that at the peak position, 33 K. This is because H II regions are lopsided to the northern part of the GMC-B, and then young massive OB stars can heat only the northern part, including the peak position, of this GMC.

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**Fig. 1.** Observed $2' \times 2'$ area with the NRO 45-m telescope superposed on Hα image obtained with SUBARU telescope of NGC 604.

| Line       | $^{13}\text{CO}(J = 1 - 0)$ | $^{12}\text{CO}(J = 1 - 0)$ | $^{12}\text{CO}(J = 3 - 2)$ |
|------------|-----------------------------|-----------------------------|-----------------------------|
| Telescope  | NRO 45-m                    | NRO 45-m                    | ASTE 10-m                   |
| Mapping mode | on-the-fly                  | on-the-fly                  | on-the-fly                  |
| Effective angular resolution | $20''$                      | $20''$                      | $25''$                      |
| r.m.s. noise level ($\Delta v = 2.5$ km s$^{-1}$) | $25 - 30$ mK               | $\sim 50$ mK               | $\sim 70$ mK               |
| Reference | this work                   | Miura et al. (2010)         | Tosaki et al. (2007a)       |

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Fig. 2. Integrated intensity map in $^{13}$CO($J = 1 - 0$) line emission (contour) superposed on that in $^{12}$CO($J = 1 - 0$) line emission (color). The contour levels are 2, 4, and 6 $\sigma$, where $1 \sigma = 0.18$ K km s$^{-1}$. The X mark indicates a point where $^{13}$CO($J = 1 - 0$) and $^{12}$CO($J = 1 - 0$) spectra are shown in figure 3.

Fig. 3. Spectra of $^{12}$CO($J = 1 - 0$) line emission (black) and $^{13}$CO($J = 1 - 0$) line emission (dashed green) at $\alpha = 1^h 34^m 33^s 20, \delta = 30^\circ 47' 06''$ (J2000), corresponding to the position of the X mark shown in figure 2. Two velocity components are seen in both profiles.
Fig. 4. Integrated intensity map in $^{13}\text{CO}(J = 1 - 0)$ line emission in NGC 604, separating two velocity components. The contour levels are 2 and 3 $\sigma$, where $1 \sigma = 0.11 \text{ K km s}^{-1}$ for the red component ($-230$ to $-210 \text{ km s}^{-1}$), and 3, 5, and 7 $\sigma$, where $1 \sigma = 0.14 \text{ K km s}^{-1}$ for the blue component ($-260$ to $-230 \text{ km s}^{-1}$).

Table 2. Line ratios and physical parameters for each GMC

| GMC label | GMC-A averaged | GMC-B averaged | peak position |
|-----------|----------------|----------------|---------------|
| line ratio |                |                |               |
| $R_{13/12}$ | $0.06 \pm 0.01$ | $0.11 \pm 0.01$ | $0.09 \pm 0.02$ |
| $R_{31}$    | $0.31 \pm 0.04$ | $0.67 \pm 0.02$ | $0.76 \pm 0.06$ |
| physical properties |             |                |               |
| $n(\text{H}_2) \text{[cm}^{-3}]$ | $7.9^{+2.4}_{-1.6} \times 10^2$ | $2.5\pm0.3 \times 10^3$ | $2.8^{+1.7}_{-0.8} \times 10^3$ |
| $T_K \text{[K]}$ | $22^{+9}_{-4}$ | $25\pm2$ | $33^{+9}_{-5}$ |
Fig. 5. (a) Integrated intensity map in $^{13}$CO($J = 1 - 0$) line emission (contour) superposed on that in $^{12}$CO($J = 1 - 0$) line emission (color) for the red component. The contour levels are the same as those for the red component in figure 4. (b) Same as (a) but for the blue component. The contour levels are the same as those for the blue component in figure 4. The cross symbol indicates the $^{12}$CO($J = 1 - 0$) peak position ($1^{h}34^{m}33^{s}42, 30^\circ 46'51''00$) of the GMC-B, and the star symbol indicates the position of the central star cluster. (c) Integrated intensity map in $^{12}$CO($J = 3 - 2$) line emission (contour) superposed on that in $^{12}$CO($J = 1 - 0$) line emission (color) for the red component. The contour levels are 3 and 5 $\sigma$, where $1 \sigma = 0.48$ K km s$^{-1}$. (d) Same as (c) but for the blue component. The contour levels are 3, 6, 9, and 12 $\sigma$, where $1 \sigma = 0.55$ K km s$^{-1}$. (e) Integrated intensity map in $^{13}$CO($J = 1 - 0$) line emission (contour) for the red component superposed on a map of H$\alpha$ luminosity (color). The contour levels are the same as (a). (f) Same as (e), but for the blue component. The contour levels are the same as (b).
Fig. 6. Curves of constant $R_{13/12}$ (black) and $R_{31}$ (red) as functions of gas density and kinetic temperature. CO fractional abundance per unit velocity gradient $Z(\text{^{12}CO})/dv/dr$ was assumed to be $1 \times 10^{-5}$, where $Z(\text{^{12}CO})$ is defined as [CO]/[H$_2$], and the unit of $dv/dr$ is km s$^{-1}$ pc$^{-1}$. The $[^{13}\text{CO}]/[^{12}\text{CO}]$ abundance ratio was assumed to be 0.02. Dashed lines indicate $\pm 1 \sigma$ error of each line ratio.
**Fig. 7.** Distributions of dense gas forming regions (black-dashed) and H II regions (black-solid) based on Tosaki et al. (2007a), superposed on figure 5(b). Here, we regard areas whose Hα luminosity exceeds $1 \times 10^{-12}$ erg s$^{-1}$ cm$^{-2}$ as H II regions. Dense gas forming regions, which are traced by high $R_{31} (> 0.7)$ arc, cover most of the GMC-B, whereas H II regions are confined in the northern part of the GMC. The central cross indicates the $^{12}$CO($J = 1 - 0$) peak position of the GMC.