CO(2–1)/CO(1–0) Line Ratio on a ~100 Parsec Scale in the Nearby Barred Galaxy NGC 1300

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Abstract

CO(2–1) emission is often used as a tracer of giant molecular clouds (GMCs) as an alternative to CO(1–0) emission in recent years. Therefore, understanding the environmental dependence of the line ratio of CO(2–1)/CO(1–0), R21, on the GMC scale is important to accurately estimate the mass of GMCs. We thus measured R21 in the strongly barred galaxy NGC 1300, where star formation activity strongly depends on galactic structure, on a ~100 pc scale. CO images were obtained from the Atacama Large Millimeter/submillimeter Array and the Nobeyama 45 m telescope. The resultant typical R21 in NGC 1300 is 0.57 ± 0.06. We find environmental variations in R21; it is the highest in the bar-end region (0.72 ± 0.08), followed by arm (0.60 ± 0.07) and bar regions (0.50 ± 0.06). GMCs with Hα emission show a systematically higher ratio (0.67 ± 0.07) than those without Hα (0.47 ± 0.05). In the bar region, where massive star formation is suppressed, Hα emission is not associated with most GMCs, resulting in the lowest R21. These results raise a possibility that properties of GMCs derived from CO(2–1) observations with the assumption of a constant R21 are different from those derived from CO(1–0) observations. Furthermore, we find the R21 measured on the kiloparsec scale tends to be lower than that of the GMCs, probably due to the presence of an extended diffuse molecular gas in NGC 1300.

Unified Astronomy Thesaurus concepts: Giant molecular clouds (653); Star formation (1569); Interstellar medium (847); Molecular gas (1073); Barred spiral galaxies (136); CO line emission (262)

1. Introduction

Giant molecular clouds (GMCs) are crucial components for understanding galactic-scale star formation because they are the nurseries for stars. The most abundant molecule in the GMCs is molecular hydrogen (H2). However, as is well known, H2 in GMCs is hardly observable in emission. This is because H2 has no permanent dipole moment and no corresponding dipolar rotational transitions. Furthermore, the lowest quadrupole rotational transition and vibrational transition of H2 are rarely observed due to the high excitation energy. Unlike H2, carbon monoxide (CO), which is the second most abundant molecule in GMCs, has a permanent dipole moment. Since the moment of inertia of CO is much larger than that of H2, CO has a low excitation energy for the lowest rotational transition J = 1–0 of E/k ~ 5.5 K, which is below the typical GMC temperature (~10–40 K; e.g., Scoville & Sanders 1987). Furthermore, the critical density for CO(1–0) is reduced to ~200–300 cm^-3 by photon trapping due to its high optical depth, which is roughly comparable to the average density within the GMCs (Solomon et al. 1987). Therefore, CO is easily excited to J = 1, and CO(1–0) is the most useful tracer of the bulk distribution of H2 in the GMCs.

The properties of GMCs have been investigated by CO(1–0) observations. In the Milky Way, molecular gas mass, size, and velocity dispersion of the GMCs are found to be typically ~10^4–6 M☉, ~20–100 pc, and 2–10 km s^{-1}, respectively (e.g., Solomon et al. 1987; Heyer et al. 2009; Miville-Deschênes et al. 2017). It has been reported that the properties of GMCs in the Local Group galaxies and nearby dwarf galaxies are similar to those of the Milky Way; e.g., M31 (Rosolowsky 2007), M33 (Rosolowsky et al. 2003), and IC10 (Ohta et al. 1992; Leroy et al. 2006). Further, extragalactic GMCs are detected on the ~50 pc scale by CO(1–0) observations with the Plateau de Bure Interferometer and the Atacama Large Millimeter/submillimeter Array (ALMA), and the environmental dependence of those properties have been investigated; e.g., M51 (Colombo et al. 2014), M83 (Hirota et al. 2018), and NGC 1300 (Maeda et al. 2020a).

To detect GMCs, the higher excitation transition of CO(2–1) emission is sometimes used to achieve a high spatial resolution as an alternative to CO(1–0); (e.g., Gratier et al. 2012; Utomo et al. 2015; Wu et al. 2017). Furthermore, in recent years, CO(2–1) has often been used in ALMA observations because CO(2–1) observations require much less time than CO(1–0) to achieve the same mass sensitivity at the ALMA site. Using CO(2–1) data of a large sample of nearby galaxies (e.g., PHANGS-ALMA; Leroy et al. 2021), statistical studies of the properties of GMCs have been conducted (e.g., Sun et al. 2018; Rosolowsky et al. 2021). In such studies, molecular gas mass is often derived from CO(2–1) luminosity by assuming a constant CO(2–1)/CO(1–0) ratio (hereafter, R21). The brightness temperature ratio of R21 = 0.65–0.8 is usually assumed based on statistical studies of R21 in nearby galaxies (e.g., Leroy et al. 2009, 2013; Sandstrom et al. 2013; Saintonge et al. 2017; den Brok et al. 2021).

However, there are two problems with the assumption of a constant R21. The first is that R21 can vary depending on...
environments in galaxies. The upper-level energy temperature and critical density of CO(2–1) emission are \(E/k \sim 16.5\, \text{K} \) and \(\sim 10^{3−4}\, \text{cm}^{-3}\), respectively, which are (slightly) higher than those of typical values of GMCs. Therefore, \(R_{21}\) can be influenced by the temperature and density of H\(_2\) gas. In the Milky Way, \(R_{21}\) in the central region is \(\sim 0.96\) is higher than the typical value in the Galactic disk of 0.6–0.7, which is interpreted as an indicator of a higher temperature and density of H\(_2\) gas in the central region (e.g., Sawada et al. 2001). Such a tendency for \(R_{21}\) to be higher in central regions than in disks was also observed in nearby galaxies (e.g., Braine & Combes 1992; Leroy et al. 2009, 2013; Yajima et al. 2021). The \(R_{21}\) also changes inside the disk. In the Milky Way, \(R_{21}\) varies from \(\sim 0.75\) at 4 kpc to \(\sim 0.6\) at 8 kpc in Galactocentric distance (Sakamoto et al. 1995, 1997). Furthermore, \(R_{21}\) in interarm regions and bar regions, where star formation activity is low, tends to be lower than that in spiral arms and bar-end regions (e.g., Koda et al. 2012, 2020; Muraoka et al. 2016; Maeda et al. 2020b). According to the nonLTE analysis, gas in the interarm region should be colder and less dense than in the spiral arms (Koda et al. 2012).

The second problem is that the assumption is based on the CO observations on kiloparsec scales, not on GMC scales (i.e., \(<\,100\, \text{pc}\)). Molecular gas traced by CO(1–0) would consist of GMCs and extended diffuse molecular gas (e.g., Snow & McCall 2006; Liszt & Pety 2012; Shetty et al. 2014). It was reported that more than 50% of the total molecular gas is diffuse gas that is distributed on scales larger than a subkiloparsec (e.g., Pety et al. 2013; Caldu-Primo et al. 2015; Maeda et al. 2020b; Patra 2021). Although the contribution of the diffuse gas is small in GMC observations, this component substantially contributes to the total CO flux in observations on kiloparsec scales and can lower \(R_{21}\) due to its low density. Therefore, \(R_{21}\) can depend on the scale (beam size), and thus measurements of \(R_{21}\) on GMC scales are indispensable. In the Milky Way, \(R_{21}\) measurements on GMC scales or a scale that can resolve GMCs have been made (e.g., Sakamoto et al. 1994, 1997; Oka et al. 1996; Seta et al. 1998; Nishimura et al. 2015). However, there are only a few examples of \(R_{21}\) measurements on GMC scales in nearby galaxies; e.g., the LMC (Sorai et al. 2001), M33 (Druard et al. 2014), and NGC 628 (Hererra et al. 2020).

For these reasons, it is urgent to investigate the environmental dependence of \(R_{21}\) on the GMC scale. In this paper, we present \(R_{21}\) in the nearby strongly barred galaxy NGC 1300 (Figure 1) on a \(\sim 100\, \text{pc}\) scale using ALMA and the 45 m single-dish telescope of Nobeyama Radio Observatory (NRO).\(^6\) This is the first study of \(R_{21}\) on the \(\sim 100\, \text{pc}\) scale in a nearby barred galaxy. In NGC 1300, unlike in the arm regions, star formation activity in the bar region is suppressed despite the presence of GMCs (Maeda et al. 2020a). Since such significant differences in star formation activity are seen, NGC 1300 is thought to be an ideal laboratory to unveil the impact of the galactic environment on \(R_{21}\). \(R_{21}\) in NGC 1300 was already measured at a 1.67 kpc resolution by Maeda et al. (2020b) and a systematic variation was found: in the bar-end region, \(R_{21}\) is the highest (\(\sim 0.7\)), followed by the arm region (\(\sim 0.4–0.6\)), and the bar region (\(\sim 0.2–0.4\)). Our main goals are to (1) measure \(R_{21}\) on a \(\sim 100\, \text{pc}\) scale, (2) investigate its environmental dependence, (3) compare with the previous lower resolution results, and (4) investigate the influence of the assumption of a constant \(R_{21}\) on the study of GMC properties.

There are two main methods to investigate the properties of the molecular gas in the high-resolution CO image. One is the cloud identification approach, which was commonly used in previous GMC studies (e.g., Williams et al. 1994; Rosolowsky & Leroy 2006). Although this method is useful for identifying isolated structures, clump finding algorithms require a number of tuning parameters and assumptions, which are often not physically motivated. The other is the pixel-by-pixel approach, which has been often used in recent years (e.g., Sawada et al. 2012; Leroy et al. 2016; Egusa et al. 2018; Sun et al. 2018). This approach is nonparametric and can treat all detected emissions. However, this approach does not provide information on the spatial extent of the molecular gas structure. In this study, we measure the \(R_{21}\) on a \(\sim 100\, \text{pc}\) scale based on both methods to minimize systematics.

This paper is structured as follows. In Section 2, we describe our CO(1–0) observations with ALMA and the NRO 45 m. We also summarize archival CO(2–1) and H\(_\alpha\) data in this section. Then, Section 3 presents the method and result of the \(R_{21}\) measurements based on the pixel-by-pixel method. Section 4 is the same as Section 3, but based on GMC identification. Discussions and a summary are given in Sections 5 and 6, respectively. We adopt the distance of NGC 1300 of 20.7 Mpc, calculated from the systemic velocity with corrections for the Virgo cluster, the Great Attractor, and the Shapley concentration of 1511 km s\(^{-1}\) (Mould et al. 2000) and the Hubble constant of 73 km s\(^{-1}\) Mpc\(^{-1}\).

### 2. Observations and Data Reduction

#### 2.1. CO(1–0)

We made a \(^{12}\text{CO}(1–0)\) cube combining the data obtained with the 12 m array of ALMA, the 7 m array of the Morita Atacama Compact Array (ACA) of ALMA, and the NRO 45 m. The ALMA 12 m array observations were carried out as an ALMA Cycle 5 program (ID = 2017.1.00248.S, PI = F.

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\(^6\) The Nobeyama Radio Observatory (NRO) is a branch of the National Astronomical Observatory of Japan, National Institutes of Natural Sciences.
The line intensity was calibrated by the chopper wheel method. The pointing accuracy was kept within 3″. The observations were described by Maeda et al. (2020a), a brief summary is given here. Two pointings were set in order to cover the western bar, arm, and bar-end regions; the field of view (FoV) within the primary beam correction factor smaller than 2.0 is shown as a blue dashed line in Figure 1. About 44 antennas were used with C43-5 configuration in which the projected baseline length ranged from 15.1–2.5 km, corresponding to a maximum recoverable scale (MRS) of ~21″4 at 115 GHz. Bandpass and phase were calibrated with J0423-0120 and J0340-2119, respectively. The Precipitable Water Vapor (PWV) was typically 1–5 mm during the observations.

The ACA 7 m array observations were performed in ALMA Cycle 7 (program ID = 2019.2.00139.S, PI = F. Maeda) as a follow-up observation program to obtain short-spacing data for the region observed by the 12 m array. To cover the FoV of the 12 m array observations, seven pointings were set. The FoV within the primary beam correction factor smaller than 2.0 is shown as an orange dotted line in Figure 1. The observations were conducted in 10 execution blocks, divided into seven periods (2020 January 14, 15, 16, 25, March 3, 6, 8, and 14), resulting in a total on-source time of about 8 hr. Most of these observations were performed with 11 antennas. The projected baseline length ranged from 8.9 m to 28.2 m, corresponding to an MRS of ~57″6 at 115 GHz. We used the Band 3 receiver with the central frequency of 114.669 GHz, channel width of 244.1 kHz (~0.64 km s~1), and bandwidth of 500.0 MHz (~1300 km s~1). This setup was almost the same as for the 12 m array observations. Bandpass was calibrated with J0334-4008, J0423-0120, J0519-4546, and J0522-3627. Phase was calibrated with J0348-1610. The PWV was typically 5–8 mm during the observations.

To include zero-spacing data, we used the data obtained with the NRO 45 m single-dish telescope. Since the details of the observations are described by Maeda et al. (2020b), a brief summary is given here. The observations were carried out on 2019 February 16, 17, 18, and 20. The observed area is shown as a black rectangle in Figure 1. We performed on-the-fly mapping using two sets of scans along the R.A. and decl. of the rectangle for a total on-source time of ~15 hr. We used the multibeam receiver, FOur-beam REceiver System, with the central frequency of 114.699 GHz, channel width of 488.28 kHz (~1.3 km s~1), and bandwidth of 1 GHz (~2600 km s~1) at 115 GHz. The effective angular resolution was ~16″/7. The line intensity was calibrated by the chopper wheel method. The pointing accuracy was kept within 3″ by observing an SiO maser source.

Calibrations of raw visibility data of the 12 m and 7 m array were done using the Common Astronomy Software Applications (CASA) ver. 5.1.1. and 5.6.1., respectively, and the observatory-provided calibration scripts. Imaging was made with CASA ver. 5.7.2. First, we concatenated the two calibrated-visibility data sets using the CASA task concat. Then, we reconstructed the image using the multiscale CLEAN algorithm with Briggs weighting with robust of 0.5. We generated a CO(1–0) data cube limiting the velocity range between 1100 and 2100 km s~1. We chose a channel width and pixel size of 5.0 km s~1 and 0″12, respectively, which are the same as those used by Maeda et al. (2020a). The resulting cube was imaged in the FoV of the 12 m array observations.

The NRO 45 m observation data were analyzed using the same method as in Maeda et al. (2020b), but we smoothed the spectrum by binning to 5.0 km s~1 here, not to 20.0 km s~1 as in the previous paper. We combined the interferometric and single-dish with the CASA task feather. The resultant angular resolution is 0″44 × 0″30, corresponding to 44 pc × 30 pc, with a position angle of −80°2. The resultant rms noise of the combined image without primary beam correction is 0.54 mJy beam~1, corresponding to 380 mK. We confirmed that the combined image with spatial smoothing to the beam size of the NRO 45 m reproduces the total flux measured with the NRO 45 m data alone.

2.2. Archival Data

2.2.1. CO(2−1)

We made a 12CO(2–1) cube using the archival data that was observed with 12 m array and ACA (7 m + Total Power) under project 2018.1.01651.S (PI = A. Leroy) and 2015.1.00925.S (PI = B. Guillermo), respectively. These observations were part of PHANGS-ALMA project (Leroy et al. 2021). This project mapped the whole disk of 90 nearby massive star-forming galaxies in CO(2–1) at an angular resolution of about 1″. The FoV within the primary beam correction factor smaller than 2.0 is shown as a green dashed–dotted line in Figure 1. The band and channel widths were set to be about 1.0 GHz (~1300 km s~1) and 244.14 kHz (~0.32 km s~1) for each observation. For the 12 and 7 m array observations, we calibrated raw visibility data using CASA and the observatory-provided calibration scripts. After concatenating the two calibrated-visibility data sets, we reconstructed the image using the multiscale CLEAN algorithm with Briggs weighting with robust of 0.5. The velocity range, channel width, and pixel size were set to be the same as for the CO(1–0) cube. Then, using the CASA task feather, the interferometric cube was combined with the cube obtained with the Total Power. The resultant angular resolution is 1.04″ × 0.79″, corresponding to 104 pc × 79 pc, with a position angle of 86°4. The rms noise of the data cube is 4.02 mJy beam~1, corresponding to 114 mK.

2.2.2. Hα

R21 can be affected by star formation activity. In the observations on kiloparsec-scale resolutions, R21 tends to be correlated with star formation rate (SFR; e.g., Koda et al. 2012; Yajima et al. 2021). The high R21 in a high SFR region is interpreted as a result of OB stars heating molecular gas (i.e., stellar feedback), or/and star formation occurring as a result of dense molecular gas. To investigate the relation between star formation and R21 at the GMC scale, we use Hα emission, which is one of the tracers of massive star formation (i.e., H II region). We use a continuum-subtracted Hα image of NGC 1300 obtained by Maeda et al. (2020b). They made the image using archival images taken with a broadband F555W filter and a narrowband Hα filter, F658N, on the ACS of the HST. By comparing the two images in the region where Hα emission is not seen, they determined the underlying stellar continuum in the F658N image (see Section 2.3.2 in the paper for details).
2.3. Homogenization and Comparison of CO and Hα Maps

To match the spatial resolutions, the CO(1–0) cube was convolved to the beam size of the CO(2–1) cube of 1.04″ × 0.79″ by using the CASA task imsmooth. The rms noise of the convolved CO(1–0) image is 3.75 mJy beam⁻¹, corresponding to 98 mK. This is comparable to that of the CO(2–1) cube. Similarly, the Hα image was regridded to the pixel scale of the CO images and convolved to the beam size of the CO(2–1) cube.

Figures 2(a) and (b) show velocity-integrated intensities maps (i.e., moment zero map) of CO(1–0) and CO(2–1), respectively. We used CPROPS (Rosolowsky & Leroy 2006) to identify CO emission lines in the cubes, and pixels identified as so-called “islands” are included to make these moment maps (see Section 4.1 for more details). Black contours show Hα emission with 3σ, 10σ, and 20σ, respectively. As shown in this figure, CO(2–1) tends to be detected in Hα bright regions, while CO(1–0) is detected in both Hα dark and bright regions. Note that CO emission is not detected downstream of the Hα bright regions. We will discuss the evolution in physical conditions of the molecular gas in Section 5.2. In this paper, we use environmental masks defined by Maeda et al. (2020a). In Figure 2, the definitions of bar, arm, and bar-end regions are indicated with blue, red, and green polygons, respectively. Each region is determined by referring to the zeroth moment map of CO(1–0) and the V-band image. The bar region covers the dark lane and associated spurs that are connected almost perpendicularly to the dark lane. The bar-end region covers the intersection region of the bar and arm.

3. Pixel-by-pixel \( R_{21} \)

3.1. Measurement

In this section, we present the line ratio \( R_{21} \) based on a pixel-by-pixel analysis. As the spatial resolution of the data cube is ~1″ and the pixel size is 0″.12, the data cube is oversampled in the spatial direction. Therefore, we rebinned the data cube to the pixel size of 1″.20, corresponding to 120 pc. This scale is comparable to the radius of the identified GMC described in Section 4. Using the rebinned CO(1–0) and CO(2–1) cubes, we measured \( R_{21} \) in the spectrum of each pixel (line of sight) as follows. We first identified the consecutive channels in which signals are above 3σrms within the velocity range 1500–1750 km s⁻¹, where significant CO emissions were detected in previous studies (e.g., Maeda et al. 2020b). Here, the σrms is calculated in each line of sight by using line-free channels. Then, we expanded these channels to include all adjacent channels in which signals are above 1.5σrms. Note that the method of identifying emission lines here is independent of the one in Section 2.3. The velocity-integrated intensity of each pixel is defined as the sum of the identified channels. Finally, we measured \( R_{21} \) for pixels in which both CO(1–0) and CO(2–1) emissions were detected. Here, we excluded one pixel in which the difference in the intensity-weighted mean velocity of both emissions was ~75 km s⁻¹ (= 7 channels) as a false detection. Note that the difference is less than 13 km s⁻¹ (<3 channels) for all other pixels.

We estimated the observation error of the velocity-integrated intensity as \( \sigma = \sqrt{N \sigma_{\text{rms}} \Delta V} \), where \( N \) is the number of channels used in the integration, and \( \Delta V \) is the channel width of 5.0 km s⁻¹, respectively. Additionally, we considered the
In this study, we investigate the relation between Hα luminosity and $R_{21}$. The continuum-subtracted Hα image is rebinned to the pixel size of $1''20$. As for the derivation of Hα luminosity ($L_{\text{H}\alpha}$) from the Hα flux density ($f_{\text{H}\alpha}$) of the continuum-subtracted Hα image, we used the same calculation method as in Maeda et al. (2020b). The $L_{\text{H}\alpha}$ is derived as

$$L_{\text{H}\alpha} = 4\pi f_{\text{H}\alpha} D^2 C_{\text{[N II]}} 10^{0.4A_V},$$

where $f_{\text{H}\alpha}$ is the effective width of the F658N filter of 74.75 Å, $D$ is the distance to NGC 1300 of 20.7 Mpc, $C_{\text{[N II]}}$ is the correction factor to remove the [N II] emission, and $A_V$ is a correction for the dust extinction. Maeda et al. (2020b) estimated the [N II] contamination to be 21% to $f_{\text{H}\alpha}$, or $C_{\text{[N II]}} = 0.79$, considering the flux density ratio of the [N II] doublet to Hα and the transmission corrections. The dust extinction was assumed to be $A_V = 1.0$ mag, which is a typical value for integrated galaxy disks obtained by Leroy et al. (2012). Maeda et al. (2020b) compared the star formation rate (SFR) derived from $L_{\text{H}\alpha}$ assuming $A_V = 1.0$ mag and hybrid tracers (far-ultraviolet + IR) at the kpc scale and showed the difference was within a factor of 2 in Hα bright regions. Therefore, the assumption of $A_V = 1.0$ mag is generally reasonable. We identified pixels above the 3σ level as having significant Hα emissions. Here, the rms noise of the flux density in the 120 pc pixel is $7.66 \times 10^{-20}$ erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$, corresponding to $5.83 \times 10^{35}$ erg s$^{-1}$. Among the pixels where both CO(1−0) and CO(2−1) are detected, the luminosity of the significant Hα emission in the 120 pc pixel is $\log(L_{\text{H}\alpha}/(\text{erg s}^{-1})) = 36.89^{+0.27}_{-0.27}$, $36.49^{+0.04}_{-0.16}$, $36.97^{+0.30}_{-0.31}$, and $36.91^{+0.16}_{-0.24}$ in the whole region, bar, arm, and bar-end, respectively.

**3.3. Results**

Figures 3(a) and (b) show the spatial distribution of the derived $R_{21}$ and its fractional uncertainty, respectively. The number of pixels with a size of 120 pc in which both CO(1−0) and CO(2−1) emissions were detected is 239 in the whole region (34 in bar, 131 in arm, and 59 in bar-end, respectively). The median uncertainty is 20%. Figure 4(a) shows the normalized cumulative distribution function of $R_{21}$ in each environment. Figures 4(b) and (c) show the ratio of the pixels with and without Hα. Results are also summarized in Table 1.

The median $R_{21}$ in the whole region is 0.65 with a scatter of 0.19. Here, the scatter is defined as the distance to the 75th percentile from the 25th percentile (the so-called “interquartile range”, IQR). As shown in Figure 4(a), we find an environmental variation in $R_{21}$. The $R_{21}$ in the bar-end is the highest (median of 0.72), followed by the arm (0.65) and bar (0.57). The scatter is 0.17−0.20. We statistically checked the environmental variation of the $R_{21}$ distribution using the two-sided Kolmogorov–Smirnov (KS) test. We used the stats. ks_2samp function of Python’s Scipy package. As a result, the $p$-values ($p_{\text{KS}}$) are low, confirming that the $R_{21}$ is statistically different among environments: the $p_{\text{KS}}$ is $4.0 \times 10^{-5}$, $1.5 \times 10^{-3}$, and $3.4 \times 10^{-2}$ for bar versus arm, bar versus bar-end, and arm versus bar-end, respectively.

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5 https://almascience.nao.ac.jp/documents-and-tools/cycle6/alma-technical-handbook
Figure 4. $R_{21}$ measured by the pixel-by-pixel method. (a) Normalized cumulative distribution function of $R_{21}$ in the whole region and in each environment. (b) Same as panel (a), but for pixels with Hα and without Hα in the whole region. (c) Same as panel (b), but for each environment.

![Image of Figure 4](image-url)

Table 1

| Region          | w/ Hα | w/o Hα | Both   |
|-----------------|-------|--------|--------|
| Whole           | 0.69 ±0.09 | 0.59 ±0.11 | 0.65 ±0.10 |
| Bar             | 0.52 ±0.13 | 0.57 ±0.07 | 0.57 ±0.08 |
| Arm             | 0.65 ±0.08 | 0.58 ±0.12 | 0.65 ±0.10 |
| Bar-end         | 0.73 ±0.09 | 0.63 ±0.12 | 0.72 ±0.10 |

Note. $R_{21}$ is noted as $M_{H_2}^{21}/M_{H_2}$, where $M$, $D_{21}$, and $D_{75}$ are the median, the distance to the 25th percentile from the median, and the distance to the 75th percentile from the median of the number distribution, respectively.

$R_{21}$ differs depending on the presence or absence of Hα. In the whole region, the median $R_{21}$ of the pixels with Hα is 0.69 which is 0.10 higher than those without Hα of 0.59. The difference is also confirmed by $p_{KS} = 4.4 \times 10^{-5}$. The $R_{21}$ of the pixels with Hα in bar-end is the highest (median of 0.73), followed by the arm (0.68) and bar (0.52). As for the pixels without Hα, while $R_{21}$ in the arm and bar are comparable ($<0.57$), and $R_{21}$ in the bar-end ($<0.63$) tends to be slightly higher than that in the arm and bar.

Figure 5 shows the relationship between the Hα luminosity and $R_{21}$ on the ~100 pc scale. In panel (a), we find a moderate correlation for the pixels with Hα; the Spearman’s rank correlation coefficient ($\rho_s$) is 0.46. The median $R_{21}$ for the pixels with $L_{H\alpha} \leq 10^{30}$ erg s$^{-1}$ and $>10^{37}$ erg s$^{-1}$ are 0.70 and 0.81, respectively. A magenta solid line represents the best-fitting line determined by the ordinary least-squares method: $R_{21} \propto L_{H\alpha}^{0.13\pm0.20}$. Such a positive correlation has been seen in the observations on kiloparsec-scale resolutions (e.g., Koda et al. 2012; Leroy et al. 2021; Yajima et al. 2021). Leroy et al. (2021) show the relationship of $R_{21} \propto \Sigma_{SFR}^{0.129}$, which is comparable to our results. This correlation is still seen if we divide the pixels into arm and bar-end (Figure 5(b)). The $\rho_s$ is 0.44 and 0.50 in the arm and bar-end, respectively. The slope in the bar-end ($R_{21} \propto L_{H\alpha}^{0.17\pm0.44}$) seems to be steeper than that in the arm ($R_{21} \propto L_{H\alpha}^{0.11\pm0.24}$). However, the significance of the difference is unclear because of the large scatter. Although it is unclear if there is a correlation in the bar because of the small number of data points, the Hα luminosity in the bar is low ($\sim(2-3) \times 10^{36}$ erg s$^{-1}$) compared to the arm and bar-end. This is the reason why the $R_{21}$ of the pixels with Hα in the bar shows lower values (Table 1).

We also investigated relationships between $R_{21}$ and the velocity-integrated intensity of CO(1–0) and CO(2–1) emissions ($I_{CO(1-0)}$ and $I_{CO(2-1)}$). $I_{CO(1-0)}$ is proportional to the molecular gas surface density. On kiloparsec scales, $R_{21}$ increases weakly with the gas surface density (e.g., Koda et al. 2012; Yajima et al. 2021). However, as shown in Figure 6(a), such a correlation is not seen in NGC 1300 on the ~100 pc scale ($\rho_s = -0.17$). While $R_{21}$ appears to increase weakly with $I_{CO(2-1)}$ (Figure 6(b)), the $\rho_s$ is low (0.31). Furthermore, no clear correlation was found between $R_{21}$ and the line width of the CO emissions. The $\rho_s$ are $-0.27$ and 0.27 for CO(1–0) and CO(2–1), respectively. We confirmed that no clear correlation between $R_{21}$ and velocity-integrated intensity (or line width) of the CO emissions appears if we separate the pixels according to environment.

3.4. Stacking Analysis

Since we used the pixels with significant CO(2–1) emissions, the above $R_{21}$ would be biased toward the CO(2–1) bright regions. In fact, we used only about half (239 pixels, 54.9%) of the total 435 pixels in which CO(1–0) was detected. In particular, as can be seen from Figure 2(b), CO(2–1) tends to be weak in the region in which significant Hα emission is not seen. Therefore, there is a possibility that the pixel-by-pixel method overestimates the median $R_{21}$. In this section, to assess the bias, we stack the CO spectra using all of the pixels in which CO(1–0) was detected.

We perform a velocity-alignment stacking analysis originally proposed by Schruba et al. (2011, 2012). This method is commonly adopted for CO spectra to measure the mean value in nearby galaxies (e.g., Morokuma-Matsui et al. 2015; Muraoka et al. 2016; Yajima et al. 2021). For CO(1–0) emission, we stacked the spectra with velocity axis alignment based on the intensity-weighted mean velocity ($\bar{v}_{CO(1-0)}$) calculated from each spectrum. For CO(2–1) emission, we stacked the spectra using the same method as for CO(1–0). For the spectra without a CO(2–1) detection, we stacked the spectra based on $\bar{v}_{CO(1-0)}$. Finally, we calculated $R_{21}$ using both stacked spectra in the same way as in the pixel-by-pixel method (see Section 3.1). The absolute flux calibration accuracy mainly contributes to the uncertainty of the stacked $R_{21}$. We also calculated the stacked $R_{21}$ by dividing the pixels into those with and without Hα. Figure 7 shows the stacked CO spectra. Black lines and orange hatched regions indicate CO(1–0) and CO(2–1), respectively. The resultant $R_{21}$ is listed in Table 2.

Here, we compare the $R_{21}$ derived by the pixel-by-pixel method with those by the stacking analysis (see also Section 5.1). For the pixels with Hα, CO(2–1) was detected in most of the pixels: the percentage of CO(2–1) detection
(f_{w/CO21}) is high in all regions (~60%–90%). Thus, the stacked $R_{21}$ is comparable to or about 0.05 lower than the median of $R_{21}$ by the pixel-by-pixel method. That said, for the pixels without Hα, $f_{w/CO21}$ is $\lesssim 50\%$. The stacked $R_{21}$ is 0.08–0.12 lower than the median of $R_{21}$ by the pixel-by-pixel method. That is, the pixel-by-pixel method is likely to overestimate the median of the pixels without Hα.

For all pixels in which CO(1–0) was detected, $f_{w/CO21}$ is 54.9%, 37.1%, 64.5%, and 80.8% in the whole region, bar, arm, and bar-end, respectively. The pixel-by-pixel method is likely to overestimate the median of the pixels in these regions, where $f_{w/CO21}$ is not high; the stacked $R_{21}$ is 0.05–0.08 lower than the median of $R_{21}$ by the pixel-by-pixel method, while both values are comparable in the bar-end. The cause for the large difference of 0.08 in the whole region is that the stacked $R_{21}$ includes not only the results in the bar and arm, but also in the interarm region (i.e., outside the three environments) where $f_{w/CO21}$ is low (21.7%).

### 4. $R_{21}$ of GMCs

#### 4.1. Identification and Measurements

In this section, we present the $R_{21}$ measured by identifying GMCs. We used the CO data cubes and Hα image with the pixel size of 0′′12. First, using the 3D clump finding algorithm CPROPS (Rosolowsky & Leroy 2006), which is designed to identify GMCs well even at low sensitivities, we identified GMCs in the CO(1–0) cube.

CPROPS begins with the identification of regions with significant emissions within the data cube (so-called islands). CPROPS identifies pixels in which the signal is above $4.0\sigma_{\text{rms}}$ in at least two adjacent velocity channels, where $\sigma_{\text{rms}}$ is the rms noise of the data cube. These islands are extended to include all adjacent pixels above $1.5\sigma_{\text{rms}}$. The parameters we used in CPROPS are THRESHOLD = 4.0 and EDGE = 1.5. We called the NONUNIFORM flag because the noise in the CO(1–0) data cube is nonuniform due to the primary beam correction. Thus, $\sigma_{\text{rms}}$ is calculated for each line of sight. The velocity-integrated intensity map of the islands of the CO(1–0) emissions is shown in Figure 2(a). Then, the islands are divided into individual GMCs using a modified watershed algorithm. CPROPS searches for local maxima within a box of three times the beam and channel width. All local maxima are required to lie at least $2\sigma_{\text{rms}}$ above the merge level with another maximum.

In this study, each local maximum is assigned to an individual GMC using a modified watershed algorithm. CPROPS searches for local maxima within a box of three times the beam and channel width. All local maxima are required to lie at least $2\sigma_{\text{rms}}$ above the merge level with another maximum. In this study, each local maximum is assigned to an individual independent cloud by setting SIGDISCONT to be 0.0. Note that these parameters in CPROPS are the same as those adopted in Colombo et al. (2014) and Maeda et al. (2020a).

A total of 111 GMCs were identified by CPROPS. Figure 8 shows the spatial distribution of the GMCs. We identified 19,
Based on CPROPS measurements, the radius $R$, the total masked CO $\alpha$ fraction, channel width, respectively. Although the CO-to-H$_2$ conversion factor, $\epsilon$, was detected in 85 of 111 GMCs shown as red ellipses in Figure 7. The Astrophysical Journal, 2022 February 10 Maeda et al.

55, and 18 GMCs in the bar, arm, and bar-end, respectively. Based on CPROPS measurements, the radius ($R$), velocity dispersion ($\sigma_v$), and molecular gas mass ($M_{mol}$) of 111 GMCs range $105.4^{+33.3}_{-19.3}$ pc, $5.9^{+1.8}_{-1.6}$ km s$^{-1}$, and $1.8^{+1.1}_{-0.8} \times 10^6 M_{\odot}$, respectively. The $R$ and $\sigma_v$ are deconvolved by the beam and channel width, respectively. Although the CO-to-H$_2$ conversion factor, $\alpha_{CO}$, may depend on environments as discussed in Section 5.4, we assumed the standard $\alpha_{CO}$ of 4.4 $M_{\odot}$ (K km s$^{-1}$ pc$^2$)$^{-1}$ (Bolatto et al. 2013) here.

For each GMC, we measured the velocity-integrated CO (1–0) intensity as the sum of the intensities of the pixels identified as the GMC. Note that CPROPS can correct for the sensitivity by extrapolating the flux to that we would expect to measure with perfect sensitivity (i.e., 0 K), but we did not make this correction here. Then, in the CO (2–1) data cube, we extracted the pixels at the position of the identified GMCs. We determined that CO (2–1) was detected in the GMC if there is at least one pixel with a signal-to-noise ratio, $S/N \geq 4$, CO (2–1) was detected in 85 of 111 GMCs shown as red ellipses in Figure 8 (12, 47, and 16 in the bar, arm, and bar-end, respectively). The sum of the CO (2–1) intensities in the pixels is defined as the velocity-integrated CO (2–1) intensity of the GMC. Finally, we measured $R_{21}$ for the GMCs using both velocity-integrated intensities. Considering the rms noise and absolute flux calibration accuracy, the median uncertainty is 14%. Figure 9 shows the properties of the GMCs in which $R_{21}$ was measured. In this study, while CO (2–1) was detected in most of the GMCs with the peak temperature ($T_{\text{max}}$) above 1.0 K, it was not detected in 43% of the GMCs with $T_{\text{max}} \leq 1.0$ K. In particular, CO (2–1) was detected in only 28% GMCs with $M_{mol} \leq 7.0 \times 10^5 M_{\odot}$. Conversely, $R_{21}$ was successfully determined for the most (86%) of the GMCs with $M_{mol} > 7.0 \times 10^5 M_{\odot}$.

4.2. Results

Figure 10(a) shows the normalized cumulative distribution function of $R_{21}$ in each environment. Figures 10(b) and (c) show $R_{21}$ of the GMCs with and without H$\alpha$. Results are also summarized in Table 3. The median $R_{21}$ of the GMCs in the whole region is 0.58 with a scatter of 0.16. As with the results of the pixel-by-pixel method, environmental variations in $R_{21}$ are seen. The $R_{21}$ in the bar-end is the highest (median of 0.68), followed by the arm (0.60) and bar (0.48). The scatter is 0.14–0.20. These differences are also confirmed by the K–S tests: $p_{KS} = 8.9 \times 10^{-3}$, $1.4 \times 10^{-3}$, and $3.5 \times 10^{-2}$ for the bar versus arm, bar versus bar-end, and arm versus bar-end, respectively.

Significant H$\alpha$ emissions (i.e., above 3$\sigma$) overlap in 67 of the 85 GMCs. In the bar and arm, 4 (21%) and 38 (69%) GMCs overlap with H$\alpha$ emission. In the bar-end, all GMCs overlap with H$\alpha$ emission. As with the results of the pixel-by-pixel method, $R_{21}$ of the GMCs with H$\alpha$ tends to be higher than that for those without H$\alpha$. In the whole region, the median $R_{21}$ of the GMCs with H$\alpha$ of 0.59 is 0.13 higher than the value for those without H$\alpha$ of 0.46 (Figure 10(b); $p_{KS} = 3.1 \times 10^{-3}$). The same trend can be seen in the arm and bar (Figure 10(c)). As for the GMCs with H$\alpha$, $R_{21}$ in the bar-end is the highest (0.58–0.72), followed by the arm (0.54–0.66) and bar (0.51–0.59). The above ratios are consistent with $R_{21}$ found by the stacking analysis (see also Section 5.1). This would be because the pixels identified as GMCs in this method include those without significant CO (2–1) emission.

As shown in Figure 11, we investigated the relationship between $R_{21}$ and GMC properties: $M_{mol}$, $R$, $\sigma_v$, and $\Sigma_{mol}$. There is no clear correlation for $R_{21}$ versus $M_{mol}$ and $\sigma_v$. $R_{21}$ is 0.15 and $-$0.15, respectively. $R_{21}$ tends to slightly decrease with increasing $R$ ($\rho_R = -0.27$). As for $\Sigma_{mol}$, we find a moderate correlation for $R_{21}$ versus $\Sigma_{mol}$: $\rho_{\Sigma} = 0.44$. The median $R_{21}$ for the GMCs with $\Sigma_{mol} \leq 100 M_{\odot}$ pc$^{-2}$ and $>100 M_{\odot}$ pc$^{-2}$ are 0.55 and 0.62, respectively.

Here, we compare our results with previous $R_{21}$ measurements toward GMCs in other galaxies. The $R_{21}$ in NGC 1300 is similar to that in the Milky Way (Sakamoto et al. 1997). In the local interarm region, where star formation activity is low, the mean $R_{21}$ of the clouds is 0.48, which is comparable to that in the bar. By contrast, the mean value is 0.68 in the Local Arm region (including Orion A and B), which is comparable to that in the bar-end and slightly higher than that in the arm. $R_{21}$ of the GMCs in the nearby grand-design spiral galaxy NGC 628 is $\sim 0.4$–0.7 (mean value of 0.54; Herrera et al. 2020), which is also comparable to that in NGC 1300. There appears to be no correlation between GMC mass and $R_{21}$ in NGC 628, which is consistent with Figure 11(a). Based on the similarity, typical physical conditions of GMCs in NGC 1300 may be similar to those in the Milky Way and NGC 628. However, a higher $R_{21}$
### Table 2

| Region    | \(f_w/\text{CO21} \pm R_{21}\) | \(f_w/\text{H}\alpha \pm R_{21}\) | \(f_w/\text{CO21} \pm R_{21}\) | \(f_w/\text{H}\alpha \pm R_{21}\) | Both          |
|-----------|-------------------------------|---------------------------------|-------------------------------|---------------------------------|---------------|
| Whole     | 78.8% (160/203) ± 0.67 ± 0.07 | 34.1% (79/232) ± 0.47 ± 0.05 | 46.7% (203/435) ± 0.57 ± 0.06 | 54.9% (239/435) ± 0.57 ± 0.06  | 0.57 ± 0.06  |
| Bar       | 62.5% (5/8) ± 0.59 ± 0.08    | 34.5% (29/84) ± 0.49 ± 0.06    | 8.7% (8/92) ± 0.50 ± 0.06     | 37.0% (34/92) ± 0.50 ± 0.06    | 0.50 ± 0.06  |
| Arm       | 80.3% (98/122) ± 0.66 ± 0.07 | 41.8% (33/79) ± 0.48 ± 0.06   | 60.7% (122/201) ± 0.60 ± 0.07 | 64.5% (131/201) ± 0.60 ± 0.07  | 0.60 ± 0.07  |
| Bar-end   | 92.3% (48/52) ± 0.73 ± 0.08  | 52.4% (11/21) ± 0.61 ± 0.08   | 71.2% (52/73) ± 0.72 ± 0.08   | 80.8% (59/73) ± 0.72 ± 0.08    | 0.72 ± 0.08  |

Note. (2) Percentage of pixels with CO(2–1) out of pixels where CO(1–0) and H\(\alpha\) were detected. (4) Same as (2), but out of the pixels where CO(1–0) is detected but H\(\alpha\) was not. (6) Percentage of pixels with H\(\alpha\) out of all pixels where CO(1–0) is detected. (7) Same as (2), but out of all pixels where CO(1–0) is detected.

## 5. Discussion

### 5.1. Environmental Variations in \(R_{21}\) on a 100 pc Scale

Here, we summarize the results based on the three analyses conducted in this study. Figure 12 compares the \(R_{21}\) on a 100 pc scale in NGC 1300 obtained by each analysis. Bars show the IQR in the panels of the pixel-by-pixel and GMC identification methods, while they show the measurement uncertainties for the stacking analysis panel. Regardless of the method, \(R_{21}\) tends to be the highest in the bar-end, followed by the arm and bar. As mentioned in Section 3.4, the pixel-by-pixel method is likely to overestimate \(R_{21}\), especially where H\(\alpha\) is not detected, because the measurement pixels are biased toward the CO(2–1) bright regions. Based on the stacking analysis and GMC identification method, the typical \(R_{21}\) in the bar-end, arm, and bar are 0.72, 0.60, and 0.50, respectively.

Our study shows that \(R_{21}\) depends on the presence or absence of H\(\alpha\) (i.e., massive star formation). The pixels (GMCs) with H\(\alpha\) have systematically higher \(R_{21}\) than those without H\(\alpha\). It is reasonable that \(R_{21}\) is high in the pixels (GMCs) with H\(\alpha\) because the gas density is so high that star formation occurs and the formed OB stars heat the gas there. In the bar, since massive star formation is suppressed (Maeda et al. 2020a), H\(\alpha\) emission is not associated with most GMCs, resulting in the lowest typical \(R_{21}\). The cause for the low star formation activity will be discussed in the next section. \(R_{21}\) of the pixels with and without H\(\alpha\) in the bar-end are higher than those in the arm, respectively, resulting in the highest typical \(R_{21}\) in the bar-end. Perhaps the gas in the bar-end is systematically denser than in the arm (see the next section).

### 5.2. Evolution in Physical Conditions of the Molecular Gas

In spiral arm structures, changes in \(R_{21}\) from low values in upstream interarm regions to high values in the downstream...
side of the spiral arms have been reported in some disk galaxies; the Milky Way (Sakamoto et al. 1997), M51 (Koda et al. 2012), and M83 (Koda et al. 2020). These results show the evolution in physical conditions of the gas as it passes through the spiral arms. In this section, we will examine if such a trend is seen in NGC 1300 using the stacking analysis.

First, the pixels with a size of 120 pc in which CO(1–0) was detected are classified into the following three types: (A) pixels in which no Hα was detected and no Hα is detected in its surrounding eight pixels, (B) pixels in which no Hα was detected but Hα is detected at least one pixel of its surrounding eight pixels, and (C) pixels in which Hα was detected (same as noted as “w/ Hα” in Table 2). Figure 13 shows the distribution of the three types of pixels. In the *arm* and *bar-end*, type A pixels (blue pixels) are distributed in the region close to the upstream interarm region. Type B (gray) and C (pink) pixels are distributed in the spiral arm structure. While Type B pixels are mostly distributed on the upstream edge of the arm, Type C pixels are mostly located downstream from Type B pixels.

We investigate the R21 for each type by using the same stacking analysis as described in Section 3.4. In the *arm*, we can see the same changes in R21 as in the spiral arm of Milky Way, M51, and M83. The stacked R21 of type A, B, and C pixels are 0.38 ± 0.05, 0.57 ± 0.07, and 0.66 ± 0.07, respectively. R21 increases from upstream interarm regions to the downstream side of the spiral arm. Compared to the difference between type A and B (0.19), the difference between type B and C is small (0.09). Based on the previous nonLTE analysis (e.g., Koda et al. 2012), the molecular gas in type A pixels, where massive star formation is not seen and R21 is low, implies that the density and temperature are lower than in the star-forming regions in the arm structure. The molecular gas of type B pixels is thought to be at the entry to the arm structure. A plausible explanation of a higher R21 in type B pixels than in type A would be that gas density is raised by compression. The temperature may also increase. Newly formed massive stars, which are obscured in their parental GMCs, may exist in the upstream edge of the Hα bright region. Surrounding massive star formation may heat the gas in type B pixels. It is reported that R21 is high in interfaces of H II regions in the Milky Way (e.g., Nishimura et al. 2015). Although H II regions are generally much smaller than the pixel size of 120 pc, such a situation might be included in type B pixels. In type C pixels, which overlap with Hα, young stellar heating would be strong, resulting in a higher R21. CO(1–0) was not detected in the downstream side of the Hα bright region. This would be because molecular gases are dispersed by feedback caused by massive star formation such as photoionization and stellar winds, which are considered to be the main mechanisms for dispersing the GMCs (e.g., Kruisjes et al. 2019; Chevance et al. 2020).

In the *bar-end*, the same trend as in the *arm* is seen. The stacked R21 of type A, B, and C pixels are 0.25 ± 0.08, 0.65 ± 0.08, and 0.73 ± 0.08, respectively. R21 of type B and C in the *bar-end* are higher than those in the *arm*. Since the LIRG, is comparable and the surface density of star formation rate

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**Table 3**

| Region     | w/ $H\alpha$ | w/o $H\alpha$ | Both |
|------------|--------------|---------------|------|
| Whole      | 0.59 ±0.08   | 0.46 ±0.12    | 0.58 ±0.08 |
| Bar        | 0.58 ±0.01   | 0.43 ±0.04    | 0.48 ±0.11 |
| Arm        | 0.61 ±0.05   | 0.48 ±0.12    | 0.60 ±0.07 |
| Bar-end    | 0.68 ±0.04   | ...           | 0.68 ±0.10 |

**Note.** Notation is the same as in Table 1.
derived from far-ultraviolet and IR data are also comparable (Maeda et al. 2020b) in both regions, there may be no difference in the heating effect. Therefore, the gas density in the bar-end may be higher than that in the arm. This is consistent with the results of recent studies that show the presence of dense gas or a high gas density in bar-end regions of the Milky Way and nearby galaxies (e.g., Gallagher et al. 2018; Yajima et al. 2019; Bešlić et al. 2021; Kohno et al. 2021). For example, in NGC 3627, Watanabe et al. (2019) showed that there is denser molecular gas in the bar-end region than in the spiral arm by comparing the chemical compositions. Kohno et al. (2021) proposed that the converging gas flow from the arm and bar causes the highly turbulent condition, which causes frequent cloud-cloud collisions (CCCs). This scenario can explain the origin of the dense gas formation, which is consistent with some simulations (e.g., Takahira et al. 2014, 2018; Renaud et al. 2015). In fact, Maeda et al. (2021) suggest that high-speed CCCs between massive GMCs occur in the bar-end of NGC 1300, which may form dense molecular gas.

The evolution of molecular gas in the bar is clearly different from that in the arm and bar-end. Unlike in those regions, most of the pixels in the bar are of type A, which is located on the dust lane. The stacked $R_{21}$ of type A, B, and C pixels are 0.44 ± 0.06, 0.54 ± 0.07, and 0.59 ± 0.08, respectively. The $R_{21}$ of type A in the bar is higher than that in the arm and bar-end. This result implies that the molecular gas in the dust lane of the bar region is denser than that in the upstream interarm regions. Nevertheless, star formation activity in the bar of NGC 1300 is clearly suppressed, as evidenced by the small number of type C pixels. Such suppression of massive star formation is seen not only in NGC 1300, but also in other barred galaxies (e.g., Downes et al. 1996; Reynaud & Downes 1998; James et al. 2009; Maeda et al. 2018, 2020a, 2020b). Some explanations have been proposed as the cause for the star formation suppression of GMCs in the bar regions: the strong shock or shear, which would make GMCs stripped, shredded, and finally destroyed (e.g., Tubbs 1982; Athanassoula 1992; Reynaud & Downes 1998; Emsellem et al. 2015), the presence of gravitationally unbound GMCs (Sorai et al. 2012; Nimori et al. 2013), and high-speed CCCs, which result in too short of a duration for the cores to grow large enough for massive star formation via gas accretion (Fujimoto et al. 2014, 2020). A recent GMC study of NGC 1300 suggests that high-speed CCCs between low-mass GMCs is the leading candidate of the cause for the suppression (Maeda et al. 2021). Note that the lower molecular gas mass in the bar would be the cause for the different star formation activity between the
bar and bar-end with the same high CCC speed (see also Sections 5.2 and 5.3 in Maeda et al. 2021).

5.3. Dependence on Spatial Scale

Maeda et al. (2020b) measured $R_{21}$ in NGC 1300 on an angular resolution of $16.7''$, corresponding to $1.67$ kpc. $R_{21}$ in the bar, arm, and bar-end are $0.26 \pm 0.02$, $0.52 \pm 0.03$, and $0.66 \pm 0.03$, respectively. These values are lower than those on the $\sim 100$ pc scale and the difference is largest in the bar; the difference from the stacking analysis (GMC identification method) is $0.24$ ($0.22$), $0.08$ ($0.08$), and $0.06$ ($0.02$) in the bar, followed by the arm and bar-end, respectively.

The cause for the low $R_{21}$ on the kpc scale would be the presence of an extended diffuse molecular gas, which is distributed on scales larger than a subkiloparsec and would not contribute to the star formation activity. Maeda et al. (2020b) measured the diffuse molecular gas fraction, which is derived using the CO(1−0) flux obtained from the ALMA 12 m array, which has no sensitivity to diffuse (extended; FWHM $\geq 700$ pc) molecular gases due to the lack of the ACA, and the total CO(1−0) flux obtained from the NRO 45 m telescope. They showed that the diffuse molecular gas fraction is $0.74$−$0.91$ in the bar and $0.28$−$0.65$ in the arm and bar-end. This indicates most of the molecular gas in the bar exists as diffuse gas. Furthermore, they find a tight anticorrelation of $R_{21}$ and the ratio of the diffuse gas, suggesting the $R_{21}$ of the diffuse gas is low. In our data cube with a high spatial resolution of $\sim 100$ pc, it is thought that such a diffuse component is too faint to be detected (even if it is detected, the GMC identification method would exclude the diffuse gas). Therefore, the pixels we used to measure $R_{21}$ in this study would not contain the majority of the diffuse gas, resulting in a higher $R_{21}$ than that measured on the kiloparsec scale. In fact, the stacked $R_{21}$ by using all pixels in the bar is roughly comparable to that on the kiloparsec scale. By predicting the $\bar{v}_{\text{CO}}$ in pixels where CO was not detected based on a velocity-field model (Maeda et al. 2021), see their Figure 2(b), the stacked $R_{21}$ in the bar is calculated to be $0.33 \pm 0.04$. This value is lower than that derived from the stacking analysis using only CO(1−0) detected pixels (Section 3.4), and is roughly comparable to that measured by Maeda et al. (2020b), which supports the idea that the majority of the diffuse CO component was not detected in our data cube with $\sim 100$ pc resolution.

Such difference between $R_{21}$ of the GMCs and that measured on the kiloparsec scale may commonly be seen in disk galaxies because a certain amount of the diffuse molecular gas is expected to universally exist in the disk galaxies as reported by some studies (e.g., Pety et al. 2013; Caldú-Primo et al. 2015). We emphasize that the difference would be large in regions with a large amount of diffuse molecular gas such as the bar in NGC 1300.

5.4. Impact of Using a Constant $R_{21}$

Molecular gas mass of a GMC is usually converted from the CO(1−0) luminosity, $L_{\text{CO}(1-0)}$, by adopting an $\alpha_{\text{CO}}$:

$$\frac{M_{\text{mol}}^{10}}{M_\odot} = \alpha_{\text{CO}} \frac{L_{\text{CO}(1-0)}}{\text{K km s}^{-1}\text{pc}^2}. \quad (2)$$

In this study, we measured $M_{\text{mol}}^{10}$ by assuming $\alpha_{\text{CO}} = 4.4 \, M_\odot$ (K km s$^{-1}$ pc$^2$)$^{-1}$ (Bolatto et al. 2013). That said, when converting the mass from the CO(2−1) luminosity, the line ratio is often assumed to be constant, $R_{21}^{\text{const}}$:

$$\frac{M_{\text{mol}}^{21}}{M_\odot} = \alpha_{\text{CO}} \frac{L_{\text{CO}(2-1)}}{\text{K km s}^{-1}\text{pc}^2}. \quad (3)$$

The $R_{21}^{\text{const}}$ of $0.65$–$0.7$ is usually assumed in recent GMC studies (e.g., Wu et al. 2017; Sun et al. 2018; Rosolowsky et al. 2021). However, $R_{21}$ of GMCs is different among environments and has a certain amount of scatter as described in Section 4. Therefore, the assumption of a constant $R_{21}$ would affect the discussion of the differences in GMC properties among environments. Here, we see the impact. To derive $M_{\text{mol}}^{21}$, we convert from $L_{\text{CO}(1-0)}$ to $L_{\text{CO}(2-1)}$ using the $R_{21}$ derived in Section 4. Then, we derived $M_{\text{mol}}^{21}$ using $R_{21}^{\text{const}}$ of $0.65$. In the same way, we derived the molecular gas surface density, $\Sigma_{\text{mol}}^{21}$, and the virial parameter, $\alpha_{\text{vir}}^{21}$. The virial parameter is a useful measure of the gravitational binding and is defined as $5\sigma_{\text{vir}}^2 R/GM_{\text{mol}}$ by Bertoldi & McKee (1992).

Figure 14 compares the physical properties obtained from CO(1−0); $(M_{\text{mol}}^{10}, \Sigma_{\text{mol}}^{10}$, and $\alpha_{\text{vir}}^{10})$ with those obtained from CO(2−1) by assuming a constant $R_{21}^{\text{const}}$ of $0.65$. Because the $R_{21}$ in the arm and bar-end is close to $0.65$, there is little difference in the cumulative distributions. By contrast, because $R_{21}$ in the bar is systematically lower than $0.65$, physical properties obtained from CO(2−1) are systematically different by $40\%$–$70\%$ compared to those from CO(1−0); the median values are $(M_{\text{mol}}^{21}, \Sigma_{\text{mol}}^{21}) = ((1.0 \times 10^{6} M_\odot, 5.9 \times 10^{5} M_\odot), (\alpha_{\text{vir}}^{21}, \Sigma_{\text{mol}}^{21}) = ((35.5 M_\odot \text{ pc}^{-2}, 21.7 M_\odot \text{ pc}^{-2}$), and $(\alpha_{\text{vir}}^{10}, \alpha_{\text{vir}}^{21}) = ((2.8, 4.7)$, respectively. Such under- or overestimations would lead to a wrong discussion of differences among environments: For example, although the environmental difference in $\alpha_{\text{vir}}^{10}$ is not seen, the $\alpha_{\text{vir}}^{21}$ in the bar seems to be higher than that in the arm and bar-end. In fact, $p_{\text{KS}}$ for the bar versus arm when using $\alpha_{\text{vir}}^{21}$ (0.13) is smaller than when using $\alpha_{\text{vir}}^{10}$ (0.44). Therefore, when comparing the properties of GMCs between environments with low star formation activity and low $R_{21}$ (e.g., a bar or interarm) and opposite environments (e.g., a spiral arm or bar-end), it is not desirable to assume a constant $R_{21}$.

It is important to note that there are other factors that can cause systematic biases in the measurement of GMC properties. There is a possibility that the $\alpha_{\text{CO}}$ changes among environments. Sorai et al. (2012) suggest that $\alpha_{\text{CO}}$ in the bar regions may be $0.5$–$0.8$ times smaller than that in the arm regions in Maffei 2 using a large velocity gradient analysis. Similar possibilities are pointed out (Morokuma-Matsu et al. 2015; Watanabe et al. 2011). Thus, molecular gas mass in the bar may be overestimated. Further, measured GMC properties depend on spatial resolution. A cloud identification algorithm tends to divide CO emission into structures with a rather uniform size scale, comparable to the spatial resolution (Hughes et al. 2013). In fact, the median radius of the GMCs in NGC 1300 is $48$ pc using the CO(1−0) cube with a $40$ pc resolution (Maeda et al. 2020a), while the median is $105$ pc in this study using a $\sim 100$ pc resolution data cube. This result suggests that the GMCs we identified are likely to be blends of smaller GMCs (in fact, the number of GMCs is approximately halved). Thus, Figure 14 would show the properties of the aggregation of multiple GMCs. To measure $R_{21}$ of GMCs more accurately, it is desirable to observe CO(2−1) with a higher spatial resolution ($\sim 40$ pc), which is a future task.
6. Summary

We measured the brightness temperature ratio of $R_{21} = ^{12}\text{CO}(2-1)/^{12}\text{CO}(1-0)$ in the strongly barred galaxy NGC 1300 on a spatial scale of ~100 pc. We observed the CO(1–0) emission using ALMA and the NRO 45 m telescope, and CO(2–1) emission was obtained from ALMA archival data. We measured the ratio not only on a pixel-by-pixel basis but also by identifying the GMCs using a 3D clump finding algorithm. In pixel-by-pixel measurements, we performed a stacking analysis. We investigated the environmental dependence of $R_{21}$ and the relationship between the ratio and star formation activity using a continuum-subtracted H$\alpha$ image. The main results are as follows.

1. Regardless of the method, $R_{21}$ tends to be the highest in the bar-end, followed by the arm and bar. The pixels (GMCs) with H$\alpha$ have a systematically higher ratio than those without H$\alpha$ (Figure 12).

(a) Based on the pixel-by-pixel analysis, which used the pixels where both CO(1–0) and CO(2–1) were detected, the resultant median $R_{21}$ is 0.65 with a scatter (i.e., IQR) of 0.19 in the whole region (Figure 4 and Table 1). We find a moderate correlation between $R_{21}$ and H$\alpha$ luminosity: $R_{21} \propto L_{H\alpha}^{0.13 \pm 0.20}$ (Figure 5).

(b) Stacking with all pixels in which CO(1–0) was detected, we find that the pixel-by-pixel method is likely to overestimate the median $R_{21}$ of the pixels without H$\alpha$. The stacked $R_{21}$ in the whole region, bar-end, arm, and bar are $0.57 \pm 0.06$, $0.72 \pm 0.08$, $0.60 \pm 0.07$, and $0.50 \pm 0.06$, respectively. In the whole region, the stacked $R_{21}$ of the pixels with H$\alpha$ of $0.67 \pm 0.07$ is higher than the value for those without H$\alpha$ of $0.47 \pm 0.05$ (Table 2).

(c) The $R_{21}$ of the GMCs, which were identified by CPROPS, is consistent with the ratio found by the stacking analysis (Figure 10 and Table 3). $R_{21}$ tends to slightly decrease with increasing GMC radius, and there is a moderate correlation of $R_{21}$ versus molecular gas surface density (Figure 11).

(d) In the bar, since massive star formation is suppressed, H$\alpha$ emission is not associated with most of the pixels (GMCs), resulting in the lowest $R_{21}$.

2. $R_{21}$ in NGC 1300 changes from low values in the upstream interarm regions to high values in downstream side of the spiral arm, which is evidence of the evolution in physical conditions of the gas as it passes through the spiral arms (Section 5.2).

3. $R_{21}$ measured on a 1.67 kpc scale tends to be lower than that on a ~100 pc scale. The cause of this difference is the presence of an extended diffuse molecular gas, which is distributed on scales larger than a subkiloparsec and would not be detected in the image with a ~100 pc resolution due to the low sensitivity. The difference between the two ratios is the largest in the bar where the diffuse molecular gas fraction is the highest in NGC 1300 (Section 5.3).

4. The assumption of a constant $R_{21} = 0.65$, which is usually used in recent GMC studies with CO(2–1) observations, tends to systematically over- or underestimate the properties of GMCs (i.e., molecular gas mass, surface density, and virial parameter) in regions where star formation activity is low (i.e., the bar). This assumption would lead to different conclusions regarding environmental variations in the properties of the GMCs than those based on CO(1–0) observations.

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Facilities: ALMA, HST, NRO:45m.
Software: CASA (ver. 5.1.1, 5.6.1, and 5.7.2), McMullin et al. (2007), NOSTAR (Sawada et al. 2008), Astropy (Collaboration et al. 2018), APLpy (Robitaille & Bressert 2012).

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