



CO Multi-line Imaging of Nearby Galaxies (COMING). II. Transitions between atomic and molecular gas, diffuse and dense gas, gas and stars in the dwarf galaxy NGC 2976

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Abstract

In this study, we present the results of ${}^{12}CO(J = 1-0)$, ${}^{13}CO(J = 1-0)$, and $C^{18}O(J = 1-0)$ simultaneous observations of the dwarf galaxy NGC 2976 conducted as a part of the CO Multi-line Imaging of Nearby Galaxies (COMING) project using the Nobeyama 45 m telescope. We investigated the properties of the molecular gas and star formation in

NGC 2976. We found that the molecular gas fraction depends on the surface densities of the total gas and the star formation rate, according to the main stellar disks of spiral galaxies. The ratio of ${}^{12}CO(J = 3-2)$ to ${}^{12}CO(J = 1-0)$ implies that the temperature of the molecular gas increases with decreases in the surface density of molecular gas. We detected 13 CO(J = 1-0) by using the stacking method. The ratio between the integrated intensities of ${}^{12}CO(J = 1-0)$ and ${}^{13}CO(J = 1-0)$ was 27 ± 11 . These ratios imply that the diffuse gas phase is dominant in low surface density regimes. We obtained a lower limit of the ratio between the integrated intensities of ${}^{12}CO(J = 1-0)$ and $C^{18}O(J = 1-0)$ of 21. The relation between the surface densities of the total gas and the star formation rate followed a power-law index of 2.08 ± 0.11 , which was larger than that between the surface densities of the molecular gas and the star formation rate (1.62 \pm 0.17). The steep slope in the relation between the surface densities of the total gas and the star formation rate can be attributed to the rapid increase in the fraction of molecular gas at the surface density of ~10 M_{\odot} . The kinematics of the molecular gas suggest that the bar-like feature rotates with a rigid-body rotation curve rather than a certain pattern speed.

Key words: galaxies: individual (NGC 2976) — galaxies: ISM — galaxies: star formation

1 Introduction

To understand the star-formation mechanism, it is essential to know the relation between the amount of interstellar gas and the star formation rate (SFR). Since Schmidt (1959) investigated the power-law relation between the volume density of interstellar gas and SFR, such relations have become an active focus of many investigations [see the reviews by Kennicutt (1998) and Kennicutt & Evans (2012)]. For example, Kennicutt (1989) studied the relation between the surface density of interstellar gas and SFR in nearby galaxies and found the threshold density at which massive star formation is suppressed. The threshold density was interpreted by a Toomre disk instability model (Toomre 1964). Recently, it has become possible to investigate the relation between the surface density of the total gas, $\Sigma(H_I) + \Sigma(H_2)$, and the surface density of the SFR, Σ_{SFR} , with a dynamic range on the order of four thanks to the drastically improved sensitivity of instruments (e.g., Bigiel et al. 2008; Schruba et al. 2011), where $\Sigma(H_{I})$ and $\Sigma(H_2)$ are the surface density of H I and H₂, respectively. Such studies have also revealed that the relation is not a single power law. That is, the power-law index is larger in the low surface density region than in the high surface density region.

To interpret the relation, a few models have been proposed (e.g., Schruba et al. 2011; Krumholz 2013; Elmegreen 2015). Schruba et al. (2011) and Krumholz (2013) attributed the change in the slope to the rapid increase in the molecular gas fraction $f_{mol} = \Sigma(H_2) / [\Sigma(H_I) + \Sigma(H_2)]$ near the surface density at which molecular gas can be shielded

against dissociation by UV radiation. Since $\Sigma(HI)$ saturates at the surface density required for the shielding, $f_{\rm mol}$ increases rapidly above the surface density (e.g., Nakanishi et al. 2006; Tanaka et al. 2014). Then, the SFR is also expected to increase rapidly above the surface density at which $\Sigma(H_I)$ saturates, since stars form from molecular gas.

On the other hand, Elmegreen (2015) argued that the change of disk thickness, that is, disk flare, is the cause of the change in slope. According to his claim, since the stellar surface density drops to less than $\Sigma(H_{I}) + \Sigma(H_{2})$ in the outer disk and dwarf galaxies, the disk thickness is determined by the gravity of the gas disk or $\Sigma(H_1) + \Sigma(H_2)$. In that case, the disk thickness increases in the outer disk and dwarf galaxies where $\Sigma(H_1) + \Sigma(H_2)$ is low. The disk flare causes the decrease in the volume density of gas, while the disk thickness is almost constant over the main stellar disks of large disk galaxies. Therefore, he suggests that the star formation rate drops rapidly in the outer disks and dwarf galaxies regardless of $f_{\rm mol}$.

These studies show that to understand the star formation relation in low gas surface density regimes ($\leq 30 M_{\odot} \text{ pc}^{-2}$), it is important to know how the gas phase (atomic gas or molecular gas) is determined and the relation between star formation and the gas phase. For such studies, observations of the outer disks of spiral galaxies or dwarf galaxies, where atomic gas is dominant, are important. Recently, studies of the interstellar medium (ISM) and star formation in low gas surface density regimes have been actively conducted. For example, Roychowdhury et al. (2015) observed the H I-dominated ISM of nearby spiral and dwarf irregular galaxies and concluded that conversion of gas to stars is independent of metallicity in such galaxies. Gross et al. (2016) investigated ISM and star formation in star-forming dwarf galaxies in the Virgo cluster. They showed that the molecular-to-atomic ratio is more tightly correlated with the stellar surface density than metallicity, and that the interstellar gas pressure plays a key role in determining the ratio. On the other hand, the number of dwarf galaxies that are spatially resolved for studies of the ISM and star formation relation is currently limited. Dwarf galaxies in the local group are important targets for such studies. For example, Leroy et al. (2006) observed IC 10 with the BIMA (Berkeley Illinois Maryland Association) interferometer. They found that the star formation relation is not consistent with the previous studies, and that the galaxy has a higher star formation rate per unit molecular or total gas than larger galaxies. Jameson et al. (2016) investigated the star formation relation in the Magellanic Clouds by using the dust continuum instead of CO. They concluded that the inclusion of a diffuse neutral medium is important for predicting the star formation rate in atomic-dominated systems like the Magellanic Clouds. While these studies provide crucial information about the star-formation relation in low gas surface density regimes, more sample galaxies are still required to get a general picture of star formation in low gas surface density regimes.

Here, we present the results of ${}^{12}CO(J = 1-0)$, ${}^{13}\text{CO}(I = 1-0)$, and $C^{18}O(I = 1-0)$ observations of NGC2976 with the Nobeyama 45 m telescope at the Nobeyama Radio Observatory (NRO). NGC 2976 is one of the best targets for studies of the star formation relation in low gas surface density regimes, as described below. Since the distance of NGC 2976 is 3.56 Mpc (Karachentsev et al. 2002), where our beam size of 15" corresponds to 255 pc, the main structure can be resolved with NRO's Nobeyama 45 m telescope. Valenzuela et al. (2014) showed that NGC 2976 has a bar-like structure with a semi-major axis of $\sim 60''$ and an offset of 20° from the disk position angle. Since atomic gas is dominant even in the main stellar disk, and the gas surface density is relatively low $(\leq 40 M_{\odot} \text{ pc}^{-2})$, the galaxy is suitable for studies of molecular gas formation and star formation with low gas surface density. Furthermore, its metallicity is close to the solar value $12 + \log O/H = 8.67$ (Schruba et al. 2011), although dwarf galaxies generally have lower metallicity than the solar value (e.g., van Zee & Haynes 2006). Therefore, we can ignore the dependence of star formation properties on metallicity and use the standard conversion factor from the ¹²CO(J = 1-0) intensity to H₂ column density, X_{CO}. The basic parameters of NGC 2976 are listed in table 1. Although there are some CO observations of

Table 1. Basic parameters of NGC 2976.

Morphological type	SAc*
Map center [†]	
$\alpha_{J2000.0}$	9 ^h 47 ^m 15 ^s .46
$\delta_{\mathrm{J2000.0}}$	+67°54′59″.0
$V_{\rm LSR} [\rm km \ s^{-1}]$	9 [§]
Distance [Mpc]	3.56∥
Inclination angle [°]	54#
Position angle of major axis [°]	143*
$D_{25}/2$ [']	$2.9 imes 1.5^{\ddagger}$

*Corwin, Buta, and de Vaucouleurs (1994).
†2MASS Large Galaxy Atlas.
§ de Vaucouleurs et al. (1991).
[§] Karachentsev et al. (2002).
[#] de Blok et al. (2008).
[‡] Buta, Corwin, and Odewahn (2007).

NGC 2976 [¹²CO(J = 1-0) via BIMA by Helfer et al. (2003), ¹²CO(J = 2-1) via the Institut de Radio Astronomie Millimétrique (IRAM) 30 m by Leroy et al. (2009), and ¹²CO(J = 3-2) via the James Clerk Maxwell Telescope (JCMT) by Tan et al. (2013)], this is the first set of mapping observations in ¹²CO(J = 1-0) made with a single-dish telescope whose angular resolution is high enough to resolve the main structure of the galaxy. ¹²CO(J = 1-0) data obtained with a single-dish telescope are very important, since ¹²CO(J = 1-0) is the most fundamental line for which we can use the standard X_{CO} to derive the surface density of molecular gas. Furthermore, a single dish can observe the total flux, while interferometers would miss extended components.

The data were taken as a part of the COMING (CO Multi-line Imaging of Nearby Galaxies) project. COMING is an imaging survey of nearby galaxies in ${}^{12}CO(J = 1-0)$, ${}^{13}\text{CO}(J = 1-0)$, and $C^{18}O(J = 1-0)$ with the multi-beam receiver FOREST (FOur beam REceiver System on the 45 m Telescope) installed on NRO's Nobeyama 45 m telescope (Minamidani et al. 2016), and it is being conducted as one of the legacy projects of NRO. With the wide bandwidth of FOREST, we can observe these three lines simultaneously. 13 CO(J = 1-0) is optically thin and traces slightly denser gas than ${}^{12}CO(I = 1-0)$. $C^{18}O(I = 1-0)$ can be used as a tracer of dense molecular gas. Therefore, these lines give us important information about the physical properties of molecular gas. The details of COMING will be described in a forthcoming paper, and Muraoka et al. (2016) investigated the relation between star formation and gas properties in NGC 2903 by using COMING data.

2 Observations and data reduction

We made simultaneous observations of ${}^{12}CO(J = 1-0)$, ${}^{13}CO(J = 1-0)$, and $C^{18}O(J = 1-0)$ emissions of NGC 2976



Fig. 1. Left: Optical three-color image, B(blue)+R(green)+I(red), of NGC 2976 from the NASA/IPAC Infrared Science Archive. Right: 12 CO(J = 1-0) integrated intensity map. The first contour and contour interval are 2 σ , where 1 $\sigma = 1.0$ K km s⁻¹. The open circle at the bottom-right corner shows the angular resolution of 18". The cross and X indicate the peaks, which coincide with both ends of the non-axisymmetric structure found by Valenzuela et al. (2014). (Color online)

with the Nobeyama 45 m telescope during 2015 April and May. The multi-beam receiver FOREST was used as the receiver front-end; it is a four-beam dual polarization receiver with side band separation mixers. The beam size was 15" 0 and 14" 0 at 110 GHz and 115 GHz, respectively, and the beam separation was 50". The mapping area was $5' \times 3'$, corresponding to 5.2 kpc \times 3.1 kpc at 3.56 Mpc. We adopted the OTF (on-the-fly) mapping mode and used two scan patterns parallel to the major axis (X scan) and minor axis (Y scan) of the galaxy. The scan separation was 4".975, and the scan speeds were $15'' \text{ s}^{-1}$ for the X scan and 9" s⁻¹ for the Y scan with a dump time of 0.1 s. We obtained scaling factors for intensity calibration by observing a standard source, IRC+10216, with each beam. Digital spectrometers of SAM45 (Spectral Analysis Machine for the 45 m telescope) were used as receiver backends. The total bandwidth and frequency resolution were 2 GHz and 488 kHz, respectively, which corresponded to 5330 km s⁻¹ and 1.3 km s⁻¹ at 115 GHz. The system temperature was 400-950 K at 115 GHz and 200-600 K at 110 GHz in T_{A}^{*} . The telescope pointing was checked every 30 min to 1 hr by using the 40 GHz receiver H40. The SiO maser source of a late-type star R-UMa was used as a pointing calibrator. Data with pointing errors of <5''were used. The chopper-wheel method was used to correct for atmospheric and antenna ohmic losses and to get the antenna temperature, T_A^* . We converted T_A^* into the main beam temperature, $T_{\rm mb}$, by using the main beam efficiency of 39% measured at 115 GHz for all lines. This was necessary because we did not have the main beam efficiency at 110 GHz for the observing season. According to the

measurements in 2016, the difference in the efficiency between 110 GHz and 115 GHz was less than 5% of the efficiency at 115 GHz and less than the errors of the measurements.¹ The absolute error of the intensity calibration was estimated to be about $\pm 20\%$. The main causes of error were variations in the efficiency of the telescope and the image rejection ratio of FOREST.

We used the NOSTAR software developed by NRO to reduce the data. After flagging bad data, image cube data were compiled for each line with a velocity resolution of 10 km s⁻¹ and pixel size of 6". Then, the linear baseline was subtracted. We determined the baseline range for the baseline fit by using ¹²CO(J = 2-1) data (Leroy et al. 2009), since the sensitivity of the ¹²CO(J = 2-1) data was better than ours. The effective angular resolution of the final map was 18" for ¹²CO(J = 1-0) and 19" for ¹³CO(J = 1-0) and C¹⁸O(J = 1-0), which corresponded to 311 pc and 328 pc at the distance of NGC 2976 (3.56 Mpc), respectively. The root-mean-square (rms) noise levels of ¹²CO(J = 1-0), ¹³CO(J = 1-0), and C¹⁸O(J = 1-0) were 44 mK, 22 mK, and 20 mK in T_{mb} , respectively, with a velocity resolution of 10 km s⁻¹.

3 Results

3.1 ${}^{12}CO(J = 1-0)$

3.1.1 Distribution and kinematics of molecular gas

Figure 1 shows the integrated intensity map of ${}^{12}CO(J = 1-0)$ with the optical image of NGC2976. The CO

¹ (http://www.nro.nao.ac.jp/~nro45mrt/html/prop/eff/eff_latest.html).



Fig. 2. Profile maps of ¹²CO(J = 1-0) around the peaks indicated by the cross (left) and X (right) marks in figure 1. The cross and X marks correspond to the center of the profile maps. The coordinates of the cross and X marks ($\alpha_{J2000.0}$, $\delta_{J2000.0}$) are (9^h47^m5^s2, 67°55′53″.0) and (9^h47^m23^s.3, 67°53′59″.0), respectively. The position interval between the profiles is 6″.

integrated intensity map shows many clumps with sizes on the order of 100 pc and masses on the order of $10^5 M_{\odot}$. The locations of the clumps roughly coincide with those of peaks of ${}^{12}CO(J = 3-2)$ (Tan et al. 2013), although the velocity-integrated intensity ratio between ${}^{12}CO(I = 3-2)$ and ${}^{12}CO(I = 1-0)$ shows some spatial variation across the mapped area. For example, there are two strong peaks, as shown by the cross and X marks in the figure, which coincide with both ends of the nonaxisymmetric structure found by Valenzuela et al. (2014). These peaks are also seen in ${}^{12}CO(J = 3-2)$. The coordinates of the peaks ($\alpha_{12000.0}$, $\delta_{12000.0}$) are (9^h47^m5^s.2, 67°55′53″.0) and (9h47m23s3, 67°53'59".0), respectively. Near the cross peak, there is another strong peak at $(\alpha_{12000.0}, \delta_{12000.0}) =$ $(9^{h}47^{m}06^{s}, +67^{\circ}55'25'')$. It is interesting that the peak is not so prominent in ${}^{12}CO(I = 3-2)$, while we can see the distinct dust lanes around this region in figure 1. Figure 2 shows the profile maps of ${}^{12}CO(I = 1-0)$ around the peaks marked with the cross and X. The main beam temperature is 0.30-0.37 K at the peak. The total flux and luminosity of 12 CO(J = 1-0) integrated over the whole observing region are 322 Jy km s⁻¹ and 1.0 \times 10⁷ K km s⁻¹ pc², respectively. The total H₂ mass derived from the ${}^{12}CO(I = 1-0)$ integrated intensity with the Galactic conversion factor $[X_{CO} = 2.0 \times 10^{20} \text{ cm}^{-2} (\text{K km s}^{-1})^{-1}; \text{ Bolatto et al. 2013}]$ is $4.3 \times 10^7 M_{\odot}$. In this estimation, we used the Galactic conversion factor since the metallicity of NGC 2976 is close to the solar value.

Figure 3 shows the ¹²CO(J = 1-0) velocity field of NGC 2976 created by the pixels with >3 σ . The iso-velocity contours are almost parallel to the minor axis of the galaxy and there is no disturbance. Figure 4 shows the position–velocity (P–V) diagram along the major axis of NGC 2976 with the position angle of 143°. The P–V diagram is very



Fig. 3. Velocity field of ¹²CO. The contours are from -61 km s⁻¹ to 79 km s⁻¹ with an interval of 10 km s⁻¹. The open circle at the bottom-right corner shows the angular resolution of 18". The solid and dashed lines indicate the lines along which the position–velocity diagrams were made in figures 4 and 14, respectively. (Color online)

simple and shows a rigid-like rotation curve up to a radius R = 100'', which corresponds to about 1.7 kpc. This result is consistent with the rotation curve of H α (Simon et al. 2003). On the other hand, the CO rotation curve in Simon et al. (2003) becomes constant at $R \sim 30''$. As Simon et al. (2003) mentioned, the discrepancy was caused by their limited mapping area, which covered only $R \lesssim 50''$. Our wider CO map made it possible to confirm that the rotation curves

of CO and H α are consistent and that the discrepancy seen in Simon et al. (2003) is a local effect.

3.1.2 Comparison with other data

Figure 5 shows the H I integrated intensity and Σ_{SFR} maps along with the ¹²CO(J = 1-0) integrated intensity map. The angular resolution of the H I and Σ_{SFR} maps are the same as the effective angular resolution of the ¹²CO(J = 1-0) map (18"). The H I map was taken from THINGS (The H I Nearby Galaxy Survey, Walter et al. 2008). The H I map shows the two brightest peaks, which coincide with the ¹²CO(J = 1-0) peaks, although the ¹²CO(J = 1-0) distribution is more clumpy than H I. Figure 6 shows the distribution of f_{mol} . Although f_{mol} is generally unity at galactic centers of nearby spiral galaxies (Tanaka et al. 2014),



Fig. 4. Position–velocity diagram along the major axis of NGC 2976. The position angle of the major axis is 143° . The first contour and contour interval are 2σ , where $1\sigma = 0.04$ K.

the highest $f_{\rm mol}$ (~0.6) was not seen at the center, but at the CO peaks with low star formation activity ($\alpha_{J2000.0}$, $\delta_{J2000.0}$) = (9^h47^m6^s, 67°55′27″), (9^h47^m12^s, 67°54′50″), and (9^h47^m19^s5, 67°54′42″). Figure 7 shows the radial distribution of $\Sigma(H_2)$, $\Sigma(H_1)$, and $\Sigma(H_1) + \Sigma(H_2)$. $\Sigma(H_1)$ is almost constant (~10 M_{\odot} pc⁻²) within R = 1.5 kpc, while $\Sigma(H_2)$ decreases gradually from the center with a bump at R = 1.1 kpc. The bump of $\Sigma(H_2)$ corresponds to the end of the non-axisymmetric structure. It is apparent that H I



Fig. 6. Distribution of f_{mol} . The open circle on the bottom-right corner indicates the angular resolution of 18". (Color online)



Fig. 5. Left: H I integrated intensity map from THINGS (color) overlaying the CO integrated intensity map (contour). Right: Σ_{SFR} derived from the FUV and 24 μ m data (color) overlaying the CO integrated intensity map (contour). The white circle on the bottom-right corner indicates the angular resolution of 18". (Color online)



Fig. 7. Radial distribution of $\Sigma(H_I) + \Sigma(H_2)$ (triangle), $\Sigma(H_2)$ (circle), and $\Sigma(H_I)$ (square). The error bars are standard deviations.

is dominant even in the inner region of NGC 2976. $f_{\rm mol}$ is ≤ 0.5 even at the center, and it is lower in the outer region. The total H I mass derived under the assumption of optically thin H I gas is $8.3 \times 10^7 M_{\odot}$, that is, about two times larger than the total H₂ mass.

Since Σ_{SFR} should account for the non-obscured and obscured star formation, it was estimated from the far UV (FUV) and 24 μ m intensities as proposed by Leroy et al. (2008). The FUV traces the photospheric emissions of massive stars and measures the star formation process not obscured by dust (Calzetti et al. 2005). On the other hand, 24 μ m emissions trace infrared(IR) emissions re-radiated by the dust grains heated by UV photons. Thus, 24 μ m emissions provide information about the obscured star formation process. To derive Σ_{SFR} , we used the FUV intensity from the GALEX Nearby Galaxies Survey (Gil de Paz et al. 2007) and the 24 μ m intensity from SINGS (The SIRTF Nearby Galaxies Survey: Kennicutt et al. 2003) to substitute values into the following equation adopted from Schruba et al. (2011):

$$\Sigma_{\rm SFR}[M_{\odot}\,{\rm yr}^{-1}\,{\rm kpc}^{-2}] = (8.1 \times 10^{-2}I_{\rm FUV}[{\rm MJy\,sr}^{-1}] + 3.2 \times 10^{-3}I_{24\,\mu\rm m}[{\rm MJy\,sr}^{-1}])\cos i, \qquad (1)$$

where I_{FUV} is the FUV intensity, $I_{24\mu m}$ is the 24 μ m intensity, and *i* is the inclination angle of the galaxy.

The two strong peaks of ${}^{12}\text{CO}(J = 1-0)$ marked with the cross and X in figure 1 coincide with the peaks in the Σ_{SFR} map. On the other hand, the star formation activity of the other CO peaks is not high ($\Sigma_{\text{SFR}} < 0.03 M_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$). This result may be indicative of significant spatial variation in the star formation efficiency within the galactic disk or differences in the evolutionary stage of the molecular



Fig. 8. ¹²CO, ¹³CO, and C¹⁸O profiles obtained by the stacking method.

clouds. The derived total SFR is $6.8 \times 10^{-2} M_{\odot} \text{ yr}^{-1}$, which is comparable to that in galaxies with similar stellar mass (e.g., Leroy et al. 2008).

3.2 13 CO(J = 1-0) and C 18 O(J = 1-0)

Since ${}^{13}CO(I = 1-0)$ and $C^{18}O(I = 1-0)$ were not detected in each pixel of the image cube at the noise levels of 22 mK and 20 mK, respectively, we tried to detect the emissions with the spectra stacking method adopted by Schruba et al. (2011) and Morokuma-Matsui et al. (2015). In this method, the spectra in the observed region are averaged after the differences of the radial velocities are canceled by using reference data for which the radial velocity can be measured. Thus, we used the intensity-weighted mean velocity of ${}^{12}CO(J = 1-0)$ as the reference velocity to remove the velocity offset in each region and obtained the averaged spectra of the ${}^{13}CO(I = 1-0)$ and $C^{18}O(I = 1-0)$ lines in the region where the ${}^{12}CO(I = 1-0)$ emission was detected with more than 3σ . Figure 8 shows the stacked profiles of ${}^{12}CO(J = 1-0)$, ${}^{13}CO(J = 1-0)$, and $C^{18}O(J = 1-0)$. The ${}^{13}CO(I = 1-0)$ emission was successfully detected with more than 3σ . The peak temperature and the rms noise level of the stacked ${}^{13}CO(I = 1-0)$ profile are 13.4 mK and 3.7 mK, respectively. The integrated intensity of the stacked 13 CO(I = 1-0) profile is 0.19 ± 0.08 K km s⁻¹, while that of the stacked ¹²CO(I = 1-0) profile is 5.1 ± 0.18 K km s⁻¹. The ${}^{12}\text{CO}(J = 1-0)/{}^{13}\text{CO}(J = 1-0)$ ratio of the integrated intensity (= R_{1213}) of the stacked profiles is 27 ± 11 . R_{1213} of the stacked profile of NGC 2976 is higher than the average value of nearby galaxies ($R_{1213} = 12-13$; Aalto et al. 1995; Davis 2014). The velocity width of the stacked ${}^{12}CO(I =$ 1-0) profile in the full width at half maximum (FWHM) is about 23 km s⁻¹, while that of the ${}^{13}CO(I = 1-0)$ profile is narrower, 15 km s⁻¹. The integrated intensity of the stacked profile is the average of the integrated intensity of the pixels used for the stacking. Therefore, we can derive the total flux and luminosity by using the integrated intensity of the stacked profile and total area of the pixels that were used for stacking. The total flux and the luminosity of 13 CO(I = 1-0) are 8.7 Jy km s⁻¹ and 3.0×10^5 K km s⁻¹ pc², respectively. The total flux of ${}^{12}CO(I = 1-0)$ derived from the stacked profile is 255 Jy km s⁻¹. Considering that the stacked profile of ¹²CO(J = 1-0) used only data with >3 σ , the flux is consistent with the total flux integrated over the whole observing region (322 Jy km s^{-1}).

Since $C^{18}O(J = 1-0)$ is a good tracer of dense molecular gas, the ${}^{12}CO(J = 1-0)/C^{18}O(J = 1-0)$ ratio can be used to examine the dense gas fraction of molecular gas. The $C^{18}O(J = 1-0)$ emission was not detected even with the stacking analysis. An upper limit of the peak temperature of $C^{18}O(J = 1-0)$ was estimated at 8.6 mK (3 σ). Thus, the lower limit of the ${}^{12}CO(J = 1-0)/C^{18}O(J = 1-0)$ ratio of the integrated intensity is 21. This lower limit is comparable to the lower limit obtained in M 51 with a 4″.5 beam, which corresponds to about 200 pc at the distance of M 51 (Schinnerer et al. 2010). The ratio observed in starburst galaxies with a 45″ beam by Aalto et al. (1995) ranged from 20 to 140, which is consistent with our lower limit. These values in external galaxies are larger than the ratio in the Galactic Giant Molecular Cloud of about 20 (Su et al. 2015).

4 Discussion

4.1 Conversion from H I to H₂

As shown in figure 7, the H I surface density is saturated at about 10 M_{\odot} pc⁻². This saturation level is consistent with that of other spiral galaxies (e.g., Crosthwaite et al. 2001; Wong & Blitz 2002; Crosthwaite & Turner 2007; Bigiel et al. 2008) and the theoretical requirement for shielding a molecular region against H₂ dissociation by UV radiation (e.g., Krumholz et al. 2009).

Figure 9 shows the relation between $\Sigma(H I) + \Sigma(H_2)$ and f_{mol} . The color of the marks indicates the Σ_{SFR} in each pixel of figure 5 (right). We can see a trend whereby f_{mol} increases with $\Sigma(H I) + \Sigma(H_2)$. The figure also shows that there is a part with relatively low f_{mol} compared to the main part of the relation. The lower part corresponds to the two highest peaks of SFR. As mentioned below, photodissociation by



Fig. 9. $\Sigma(H_1) + \Sigma(H_2)$ vs. f_{mol} . The color indicates Σ_{SFR} . The data with more than 3 σ in H I are plotted. Circles and squares indicate the data with more than 2 σ and less than 2 σ in CO, respectively. (Color online)

strong UV radiation from massive stars in star-forming regions may be the cause of the low f_{mol} .

According to the model of Elmegreen (1993), $f_{\rm mol}$ depends on metallicity, pressure, and UV radiation. High metallicity promotes the formation of molecular hydrogen on dust grains and prevents photodissociation by shielding UV radiation. Since high pressure increases the density of interstellar gas, it also promotes the formation of molecular gas and self-shielding of UV radiation. On the other hand, strong UV radiation promotes photodissociation and decreases $f_{\rm mol}$. The model assumes that there are two kinds of molecular cloud, namely diffuse clouds and selfgravitating clouds. Given the mass function of molecular clouds and radial distribution of gas density in the molecular clouds, the molecular gas mass within each molecular cloud can be calculated by considering the equilibrium equation of the balance between photodissociation and recombination. This model has been used for comparisons with the observational results for some spiral galaxies (e.g., Honma et al. 1995; Kuno et al. 1995; Nakanishi et al. 2006; Tosaki et al. 2011; Tanaka et al. 2014), and shows good agreement with the observed data. Those studies are mainly about main disks where molecular gas is dominant. We also compared our results with the model of Elmegreen (1993) to check if the basic idea is reasonable for regions with low surface densities of total gas. In this model, pressure, metallicity, and UV radiation are scaled with the solar value. We assumed that the ISM pressure is approximately proportional to the square of the gas surface density (Elmegreen 1989). To scale the pressure with the solar value, we adopted $\Sigma(H_{I}) + \Sigma(H_{2}) = 8 M_{\odot} \text{ pc}^{-2}$ (Sanders et al. 1984) as the solar value. Since the metallicity of NGC 2976 is close to the solar value, as mentioned above, we adopted the solar value $(12 + \log O/H = 8.69)$ for



Fig. 10. Comparison between f_{mol} obtained from our observations and the calculated f_{mol} with the model of Elmegreen (1993).

all regions. We used SFR as the indicator of the strength of UV radiation. $\Sigma_{SFR} = 2.7 \times 10^{-3} M_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$ of the solar neighborhood was estimated from $\Sigma(H_1) + \Sigma(H_2)$ and the star formation relation between $\Sigma(H_1) + \Sigma(H_2)$ and Σ_{SFR} from Bigiel et al. (2008). Σ_{SFR} at each pixel in NGC 2976 was derived as mentioned in sub-subsection 3.1.2 from FUV and 24 μ m data. Figure 10 shows the comparison between $f_{\rm mol}$ calculated by the model and that from our observations. Although the dispersion is large and the model results are systematically lower than the observed f_{mol} , they show that the relation between $\Sigma(H_{I}) + \Sigma(H_{2})$ and f_{mol} can be roughly reproduced by the model of Elmegreen (1993). The main cause of the large dispersion is likely the uncertainty of the estimation of the strength of the radiation field derived from the star formation law with a single power and $\Sigma(H_{I}) + \Sigma(H_{2})$. Another possible cause of the discrepancy may be the uncertainty of the estimation of the pressure (Tanaka et al. 2014).

4.2 Physical properties of molecular gas

We investigated the physical properties of molecular gas in NGC 2976 by comparisons with the ¹²CO(J = 3-2) data from Tan et al. (2013). We convolved the ¹²CO(J = 3-2) image cube (FWHM = 14″.5) to match the angular resolution to our ¹²CO(J = 1-0) data (18″). Figure 11 shows the relation between $\Sigma(H_2)$ and $R_{31} = I_{12CO(J=3-2)}/I_{12CO(J=1-0)}$. Σ_{SFR} is also indicated with a colored scale. This figure shows that R_{31} is lower than unity over the entire mapping region and that R_{31} increases with decreases in $\Sigma(H_2)$. To see the dependence of R_{31} on $\Sigma(H_2)$, that is, the change of physical properties of molecular gas with $\Sigma(H_2)$, more quantitatively, we took averages of R_{31} for $\Sigma(H_2) < 10 M_{\odot} \text{ pc}^{-2}$ and $\geq 10 M_{\odot} \text{ pc}^{-2}$. The averages of R_{31} are 0.27 ± 0.09 and 0.19 ± 0.05 for $\Sigma(H_2) < 10 M_{\odot} \text{ pc}^{-2}$ and $\geq 10 M_{\odot} \text{ pc}^{-2}$,



Fig. 11. Σ_{H_2} vs. R_{31} . The color indicates Σ_{SFR} . The dashed lines are 2 σ of CO(1–0) (vertical line) and CO(3–2) (curved line). The red and yellow stars are the average of R_{31} in 2 $\sigma \leq \Sigma_{H_2} < 10 \ M_{\odot} \ pc^{-2}$ and 10 $M_{\odot} \ pc^{-2} \leq \Sigma_{H_2}$, respectively. (Color online)

respectively. To increase R_{31} , the molecular gas has to be denser and/or warmer. It is probable that molecular gas becomes less dense with a decrease in the surface density. Therefore, the rise of R_{31} toward low $\Sigma(H_2)$ may have been caused by the rise of temperature.

If we assume local thermodynamic equilibrium (LTE), that is, the excitation temperature of ${}^{12}\text{CO}(J = 1-0)$ and ${}^{12}\text{CO}(J = 3-2)$ equal the kinetic temperature, R_{31} is given by the following equation:

$$R_{31} = \frac{T_{32}}{T_{10}} \frac{1/(e^{T_{32}/T_{\text{ex}}} - 1) - 1/(e^{T_{32}/2.73} - 1)}{1/(e^{T_{10}/T_{\text{ex}}} - 1) - 1/(e^{T_{10}/2.73} - 1)} \frac{1 - e^{-\tau_{32}}}{1 - e^{-\tau_{10}}}, \quad (2)$$

where $T_{10} = hv_{10}/k$, $T_{32} = hv_{32}/k$, v_{10} , and v_{32} are rest frequencies of ${}^{12}\text{CO}(J = 1-0)$ and ${}^{12}\text{CO}(J = 3-2)$, and τ_{10} and τ_{32} are optical depths of ${}^{12}\text{CO}(J = 1-0)$ and ${}^{12}\text{CO}(J = 3-2)$, respectively. If we assume that both lines are optically thick, the observed R_{31} corresponds to $T_{\text{ex}} \approx 4.5$ K and 3.6 K for the low $[\Sigma(\text{H}_2) < 10 \ M_{\odot} \text{ pc}^{-2}]$ and high $[\Sigma(\text{H}_2) \ge 10 \ M_{\odot} \text{ pc}^{-2}]$ density regions, respectively. The temperatures are too low compared to that of the Galactic molecular gas (Solomon et al. 1987). On the other hand, if the lines are optically thin, R_{31} must be >1 at $T_{\text{ex}} \gtrsim 12$ K. Therefore, the observed R_{31} cannot be explained with the assumption of optically thin gas either, and it is difficult to reproduce the observed R_{31} under the LTE assumption.

We used RADEX (van der Tak et al. 2007) to examine a non-LTE case and to estimate the temperature and density of a molecular gas that can reproduce the observed R_{31} . We assumed that the metallicity is constant at 12 + log O/H = 8.67 over the entire disk of NGC 2976. Since the velocity dispersion is fairly constant, as seen in figures 2 and 4, we adopted the



Fig. 12. Results of calculations by RADEX. The solid and dashed curves show the results for $2\sigma \le \Sigma(H_2) < 10 \ M_{\odot} \ pc^{-2}$ and $10 \ M_{\odot} \ pc^{-2} \le \Sigma(H_2)$, respectively. For both cases, the upper and lower curves correspond to 12 CO/H₂ abundance ratios of 10^{-5} and 10^{-4} , respectively. The open and filled rectangles indicate the ranges of the physical parameters of the diffuse gas ($T_k = 30-70 \ K$, $n = 200-500 \ cm^{-3}$) and self-gravitating cloud ($T_k = 10-15 \ K$, $n \sim 10^3 \ cm^{-3}$) in the Galaxy.

average velocity dispersion of 23 km s⁻¹. The column density of ¹²CO was derived from the ¹²CO(I = 1-0) integrated intensity assuming the Galactic X_{CO} and a 12 CO/H₂ abundance ratio of 10^{-5} – 10^{-4} (e.g., van Dishoeck & Black 1987). Figure 12 shows the results of the calculations of RADEX. The dashed and solid curves correspond to the average of R_{31} at the high $[\Sigma(H_2) > 10 M_{\odot} \text{ pc}^{-2}]$ $(R_{31} = 0.19)$ and low $[\Sigma(H_2) < 10 M_{\odot} \text{ pc}^{-2}]$ $(R_{31} = 0.27)$ surface density regions, respectively. The results show that if the volume density is higher in the high surface density region than that in the low surface density region, the temperature of molecular gas in the high surface density region has to be lower than that in the low surface density region. Therefore, the decrease in R_{31} with $\Sigma(H_2)$ may imply that there is a change of molecular gas from a diffuse gas phase with low density and high temperature to molecular clouds with high density and low temperature.

Since we used only one line ratio, we could not determine the temperature and density. Therefore, we compared our results with the physical parameters of the molecular gas observed in the Galaxy to see if we could find realistic combinations of the temperature and density of molecular gas coinciding with the curves that we derived. For selfgravitating molecular clouds, the typical kinematic temperature and density are 10–15 K and $\sim 10^3$ cm⁻³, respectively; on the other hand, those of the diffuse gas are 30–70 K and 200–500 cm⁻³, respectively (e.g., Crutcher & Watson 1981; Black & van Dishoeck 1988; Rachford et al. 2001; Liszt et al. 2009). As shown in figure 12, although the parameter ranges are slightly lower in terms of density or temperature than the curves, the range of the diffuse gas overlaps with the lower edge of the low surface density region. The range of the self-gravitating molecular gas also overlaps the lower edge of the high surface density region. Therefore, the results of the RADEX calculations do not contradict our interpretation that the increase in R_{31} at low $\Sigma(H_2)$ is caused by an increase in the temperature of the molecular gas.

Since the optical depth of ${}^{12}CO(I = 1-0)$ is expected to be moderate ($\tau \sim 1$) for the diffuse gas, R_{1213} should be higher than that for the gas with optically thick ${}^{12}CO(I =$ 1-0) (Aalto et al. 1995). Even in spiral galaxies, such diffuse gas with high R₁₂₁₃ can be observed in bar and interarm regions (Morokuma-Matsui et al. 2015). This previous work has shown that R_{1213} in the bar and inter-arm regions $(31.8 \pm 3.9 \text{ and } 24.7 \pm 2.8, \text{ respectively})$ is higher than that in the spiral arms (14.2 \pm 0.6). R_{1213} in the bar and interarm regions is comparable to that measured in NGC 2976. Our result implies that the area with the diffuse gas phase is dominant in NGC 2976 and that R_{1213} is close to that for the diffuse gas. Therefore, high R_{1213} (=27 ± 11) observed in NGC 2976 is also consistent with our interpretation that diffuse gas is dominant in the region with a low gas surface density.

We note that the uncertainty of X_{CO} may be larger in NGC 2976 than normal spiral galaxies, although we used the Galactic X_{CO} to derive the total H₂ mass. Since X_{CO} depends on the temperature *T* and density *n* as

$$X_{\rm CO} \propto \frac{\sqrt{n}}{T} \tag{3}$$

(Solomon et al. 1987), X_{CO} in the diffuse gas may be smaller than the Galactic value. On the other hand, since photodissociation of CO is effective for the diffuse gas, this brings about an increase in X_{CO} . The balance of these effects determines X_{CO} in the diffuse gas (Bell et al. 2006).

In figure 11, we can also see the trend whereby R_{31} increases with an increase in Σ_{SFR} at the same $\Sigma(\text{H}_2)$. This tendency is clearly seen above $\Sigma(\text{H}_2) > 10 \ M_{\odot} \text{ pc}^{-2}$. In particular, the highest three R_{31} (~0.35) values correspond to the points with the highest three SFR values. Star formation rate is expected to increase in regions with high gas density. On the other hand, high star formation activity is expected to raise the temperature of the surrounding molecular gas. Therefore, the rise of R_{31} is considered to have been caused by the increase of density and/or temperature related to star formation activity. Since the trend is clear above $\Sigma(\text{H}_2) > 10 \ M_{\odot} \ \text{pc}^{-2}$, the result may also imply that the dense molecular gas, which can form stars, increases rapidly above $\Sigma(\text{H}_2) > 10 \ M_{\odot} \ \text{pc}^{-2}$.

4.3 Star formation

Figure 13 shows plots of $\Sigma(H_2)$ versus Σ_{SFR} , $\Sigma(H_I)$ versus Σ_{SFR} , and $\Sigma(\text{HI}) + \Sigma(\text{H}_2)$ versus Σ_{SFR} . For $\Sigma(\text{H}_2)$ and $\Sigma(HI)$, the pixels at which ${}^{12}CO(I = 1-0)$ and H I were detected at more than 2σ are plotted. For $\Sigma(H_1) + \Sigma(H_2)$, we plotted the data that detected ${}^{12}CO(I = 1-0)$ at more than 2σ . When the data are fitted with a power law, the power law indexes are 1.62 ± 0.17 , 2.76 ± 0.11 , and 2.08 ± 0.11 for $\Sigma(H_2)$, $\Sigma(H_1)$, and $\Sigma(H_1) + \Sigma(H_2)$, respectively. The correlation coefficients for $\Sigma(H_2)$, $\Sigma(H_1)$, and $\Sigma(\text{HI}) + \Sigma(\text{H}_2)$ are r = 0.46, 0.80, and 0.75, respectively. The power law index of the correlation between Σ_{SFR} and $\Sigma(H_2)$ is consistent with many previous studies of the star formation law (Kennicutt & Evans 2012), although the dispersion is large. The correlation between Σ_{SFR} and $\Sigma(HI)$ shows a very steep slope at about 10 M_{\odot} pc⁻², which corresponds to the saturation level of the H I surface density as seen in the radial distribution. The power law index is larger than that derived in Bigiel et al. (2008) (1.78). One of the causes of the difference may be the difference in spatial resolution, since our resolution (311 pc) is more than twice as high as theirs (750 pc). Since star-forming regions in NGC 2976 are more compact than H I clouds and concentrate on the H I peaks, it is probable that a higher angular resolution will give a higher power law index. As shown in figure 5, the size of the active star-forming regions are comparable to our beam size, while H I distributes much more uniformly. Therefore, there are regions where H I is relatively strong without star formation. These regions make the slope of H I versus SFR steep. If, however, we observe H I and star-forming regions with a larger beam, the extent of the star-forming region approaches that of HI by convolving with the larger beam. Furthermore, the relative amplitude of the peak of the SFR decreases. As a result, the slope is expected to become shallower.

The correlation between Σ_{SFR} and $\Sigma(\text{HI}) + \Sigma(\text{H}_2)$ is tight and the slope is steeper than $\Sigma(H_2)$. Bigiel et al. (2008) and Schruba et al. (2011) have shown that the slope of the relation between Σ_{SFR} and $\Sigma(HI) + \Sigma(H_2)$ is very steep in low surface density regions $[\Sigma(H_{I}) + \Sigma(H_{2}) <$ 20 M_{\odot} pc⁻²]. The power law index is larger than 2 there, although the relation is close to linear at a higher surface density. On the other hand, the relation between Σ_{SFR} and $\Sigma(\text{H}_2)$ is linear even at the low surface density region. Therefore, they attributed the steep slope at the low surface density region in the relation between Σ_{SFR} and $\Sigma(H_{I}) + \Sigma(H_{2})$ to rapid change of f_{mol} . Our observing range of $\Sigma(H_{\rm I}) + \Sigma(H_2)$ ($\lesssim 40 \ M_{\odot} \ {\rm pc}^{-2}$) covers the saturation level of H I in NGC 2976 and the range of the steep slope in the star formation relation in Schruba et al. (2011) ($\leq 20 M_{\odot} \text{ pc}^{-2}$). Our results are consistent with their



Fig. 13. Top: Σ_{H_2} vs. Σ_{SFR} . Middle: Σ_{H_1} vs. Σ_{SFR} . Bottom: $\Sigma(H_1) + \Sigma(H_2)$ vs. Σ_{SFR} . The dashed lines are the results of fitting with a power law. The power law indexes are 1.62 ± 0.17, 2.76 ± 0.11, and 2.08 ± 0.11 from the top.

claim. Since molecular gas, which forms stars, increases rapidly above $\Sigma(H_{\rm I}) \sim 10 \ M_{\odot} \ {\rm pc}^{-2}$, $\Sigma(H_{\rm I})$ is nearly constant there. Therefore, $\Sigma(H_{\rm I}) + \Sigma(H_2)$ is almost $\Sigma(H_2)$ plus an offset (~ 10 $M_{\odot} \ {\rm pc}^{-2}$). As a result, the slope of the relation between $\Sigma_{\rm SFR}$ and $\Sigma(H_{\rm I}) + \Sigma(H_2)$ becomes steeper than that of the relation between $\Sigma_{\rm SFR}$ and $\Sigma(H_2)$.

On the other hand, Elmegreen (2015) proposed another interpretation of the change in the slope. He claimed that the differences of the slope in the star formation relation between main disks and outer disks or dwarf galaxies are caused by disk flare, as introduced in section 1. If the stellar surface density drops to less than the gas surface density in the outer disks and dwarf galaxies, the scale height of the gas disk is determined by the gas surface density, and the thickness of the outer disks and dwarf galaxies increases. Therefore, the average volume density and SFR are expected to decrease rapidly in the outer disks and dwarf galaxies regardless of $f_{\rm mol}$. For NGC 2976, however, the two highest peaks of SFR are located in the outer edge of the molecular gas distribution ($R \sim 70''$) rather than within the inner region. Since the locations of the SFR peaks correspond to the break of the stellar surface density between the inner stellar disk with a stellar surface density of 117.8 M_{\odot} pc⁻² and the outer stellar disk with a stellar surface density of 19.6 M_{\odot} pc⁻² (Adams et al. 2012), the stellar surface density decreases rapidly there. According to Elmegreen (2015), SFR should also decrease rapidly in such regions. Therefore, our result is inconsistent with the idea of Elmegreen (2015) in which high SFR is expected to be seen in an inner disk with a high stellar surface density and thin gas disk.

4.4 Non-axisymmetric structure

Valenzuela et al. (2014) showed that NGC 2976 has a barlike feature whose position angle is close to that of the galactic disk by using near infrared and CO data. Kuno et al. (2000) and Hirota et al. (2009) showed that barred galaxies whose position angle of the bar is close to the position angle of the galactic disk have a rigid-like rotation curve. This is because when we observe the molecular gas at the ridges along the bar, the observed velocity corresponds to the pattern speed of the bar rather than the rotation velocity of the gas. Since the difference in the position angles of the bar and the line of nodes of NGC 2976 is about 20°, it is not improbable that the rigid-like rotation curve corresponds to the pattern speed of the bar (Hirota et al. 2009). On the other hand, in that case, a large velocity jump should be found at the bar because the velocity vector of the gas changes rapidly at the ridge along the bar, as shown by the previous studies involving both observations and numerical simulations (e.g., Regan et al. 1999; Hirota et al. 2014). Actually, most barred galaxies show large distortions of iso-velocity



Fig. 14. Position–velocity diagram along the line perpendicular to the bar-like structure as shown in figure 3. The first contour and contour interval are 2σ , where $1\sigma = 0.04$ K.

contours along the bar and large velocity widths at the ridge (Kuno et al. 2007). The velocity field of NGC 2976, however, shows no large distortion as mentioned above (figure 3). Valenzuela et al. (2014) showed that H α has a velocity jump at the bar. Figure 14 shows the CO P-V diagram along the line perpendicular to the bar of NGC 2976. The velocity width at the bar is comparable to other positions and we did not see such a velocity jump at the bar-like feature in CO. These results cannot be attributed to the lower angular resolution compared with H α , since the spatial resolution is comparable to or higher than the previous CO observations in which a large velocity jump was seen at the bar (Kuno et al. 2007). In addition, even for the galaxies with such a bar configuration, the velocity dispersion in the central region of most of the barred galaxies is very large because of the X_2 orbit, which is perpendicular to the large scale bar (X1 orbit; e.g., NGC 2903 and M 83 in Kuno et al. 2007). The P-V diagram of NGC 2976, however, does not show a large velocity width even at the central region, and the velocity width is almost constant (figure 4). The H α P–V diagram in Valenzuela et al. (2014) displays some features that look like a velocity jump even at the non-bar position. Therefore, we think that the quality of the data is not good enough to say that the feature is the velocity jump due to the bar. Data with higher quality are thus required to confirm whether the velocity jump in H α is real or not. The kinematics of molecular gas, at least, suggest that the nonaxisymmetric structure rotates with a rigid-body rotation curve rather than a certain bar pattern speed as in barred spiral galaxies.

5 Summary

In this study, we presented the results of ${}^{12}CO(J = 1-0)$, ${}^{13}CO(J = 1-0)$, and $C^{18}O(J = 1-0)$ observations of the

dwarf galaxy NGC 2976 with the Nobeyama 45 m telescope. The results are summarized as follows:

- (1) The ¹²CO(J = 1-0) map has a clumpy structure. The two strong ¹²CO(J = 1-0) peaks located at each end of the non-axisymmetric structure coincide with the peaks of ¹²CO(J = 3-2) and Σ_{SFR} . Other peaks are not so active in star formation.
- (2) ¹³CO(J = 1-0) was detected by the stacking method. The ratio between the integrated intensities of ¹²CO(J = 1-0) and ¹³CO(J = 1-0), R_{1213} , is 27±11, which is about twice as high as the average value of nearby galaxies (12–13). C¹⁸O(J = 1-0) was not detected even by the stacking method. The lower limit of the ratio between the integrated intensity of ¹²CO(J = 1-0) and C¹⁸O(J = 1-0) is 21.
- (3) The ratio of molecular gas to total gas, f_{mol} , shows the dependence on the surface density of total gas, $\Sigma(HI) + \Sigma(H_2)$, and SFR surface density, Σ_{SFR} , that is, f_{mol} increases with increases in $\Sigma(HI) + \Sigma(H_2)$ and is low at the two highest peaks of Σ_{SFR} . This trend can be roughly reproduced by the model of Elmegreen (1993).
- (4) The ratio between the integrated intensities of ${}^{12}CO(J = 3-2)$ and ${}^{12}CO(J = 1-0)$, R_{31} , increases with decreases in the surface density of molecular gas, $\Sigma(H_2)$. The result implies that molecular gas changes from a diffuse phase with high temperature to self-gravitating clouds with low temperature. The high R_{1213} is also consistent with our interpretation. We also found a trend whereby R_{31} increases with increases in Σ_{SFR} when we compared data at the same $\Sigma(H_2)$.
- (5) The power-law index of Σ_{SFR} and $\Sigma(HI)$ is larger than that of the relation between $\Sigma(H_2)$ and Σ_{SFR} . The relations are consistent with the idea that the rapid conversion from HI to H₂ forms a steep slope in the relation between $\Sigma(HI) + \Sigma(H_2)$ and Σ_{SFR} .
- (6) The ¹²CO map displays a non-axisymmetric distribution, as the previous observations have shown. The kinematics of the molecular gas showed no disturbance at the feature, which suggests that it is not a bar structure with a certain pattern speed as seen in barred spiral galaxies but rotates with a rigid-body rotation curve.

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