Molecular Gas Density Measured with H$_2$CO and CS toward a Spiral Arm of M51

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Abstract

Observations of various molecular lines toward a disk region of a nearby galaxy are now feasible, and they are being employed as diagnostic tools to study star formation activities there. However, the spatial resolution attainable for a nearby galaxy with currently available radio telescopes is 10–1000 pc, which is much larger than the scales of individual star-forming regions and molecular-cloud cores. Hence, it is of fundamental importance to elucidate which part of an interstellar medium such spatially unresolved observations are tracing. Here we present sensitive measurements of the H$_2$CO (l$_{01}$ – l$_{00}$) line at 72 GHz toward giant molecular clouds (GMCs) in the spiral arm of M51 using the NRO 45 m and IRAM 30 m telescopes. In conjunction with the previously observed H$_2$CO (2$_{01}$ – 1$_{00}$) and CS (2 – 1 and 3 – 2) lines, we derive the H$_2$ density of the emitting regions to be (0.6–2.6) × 10$^5$ cm$^{-3}$ and (2.9–12) × 10$^4$ cm$^{-3}$ for H$_2$CO and CS, respectively, by the non-LTE analyses, where we assume the source size of 0.8–1 kpc and the gas kinetic temperature of 10–20 K. The derived H$_2$ density indicates that the emission of H$_2$CO and CS is not localized to star-forming cores, but is likely distributed over an entire region of GMCs. Such widespread distributions of H$_2$CO and CS are also supported by models assuming lognormal density distributions over the 1 kpc region. Thus, contributions from the widespread less dense components should be taken into account for interpretation of the molecular emission observed with a GMC-scale resolution. The different H$_2$ densities derived for H$_2$CO and CS imply their different distributions. We discuss these differences in terms of the formation processes of H$_2$CO and CS.

Key words: astrochemistry – galaxies: individual (M51) – galaxies: ISM – ISM: clouds – ISM: molecules

1. Introduction

Recently, molecular line observations in the millimeter and submillimeter wave regime have become more and more popular in extragalactic studies (e.g., Aladro et al. 2015; Meier et al. 2015; Harada et al. 2018). Thanks to the advanced instrumental capabilities of single-dish telescopes and interferometers, rotational spectral lines of various molecular species other than CO and its isotopologues can readily be detected in external galaxies. For instance, HCN and HCO$^+$, which are often employed as dense-gas ($>3 \times 10^4$ cm$^{-3}$) tracers, have extensively been observed to reveal physical conditions of a molecular gas (e.g., Gao & Solomon 2004; Usero et al. 2015; Bigiel et al. 2016; Jiménez-Donaire et al. 2017). H$_2$CO and CS are also popularly observed to measure the gas density and temperature (e.g., Mauersberger & Henkel 1989; Bayet et al. 2009; Mangum et al. 2013; Tang et al. 2017). Furthermore, molecular inventory is now being extended not only to bright central regions of galaxies but also to faint disk regions (e.g., Watanabe et al. 2014; Bigiel et al. 2016; Watanabe et al. 2019). However, the spatial resolution that can be achieved with currently available radio telescopes is 10–1000 pc even for nearby galaxies: exceptions are the nearest galaxies, such as the Large and Small Magellanic Clouds. This resolution is larger than typical sizes of star-forming regions (~0.1 pc) and giant molecular clouds (GMCs, ~1–10 pc). To make full use of molecular lines for physical and chemical diagnostics of disk regions in external galaxies, we need to know what parts of an interstellar medium the emission of the dense-gas tracers comes from. More specifically, it is important to validate whether the emission of each molecular species is exclusively localized to cloud cores or distributed also in the diffuse regime.

There are two approaches to this problem. One approach is to conduct a large-scale mapping observation toward Galactic GMCs with various molecular lines, and to evaluate a fraction of the emission coming from each part of the GMCs (i.e., star-forming cores, their envelopes, and cloud peripheries) for each molecular line when the line is observed with a large beam covering a whole GMC. This approach is being conducted in several GMCs (Kauffmann et al. 2017; Nishimura et al. 2017; Pety et al. 2017; Watanabe et al. 2017; Harada et al. 2019). These studies indicate a significant contribution of the emission from less dense regions even for “dense-gas” tracers such as HCN, HCO$^+$, and CS. The other approach, which is directly applicable for extragalactic sources, is to measure the gas density of the emitting region by multiline observations. So far, multiline observations have been conducted toward central regions of galaxies (e.g., Aladro et al. 2011b). On the other hand, such observations are very challenging toward disk regions because molecular lines are fainter (e.g., Usero et al. 2015; Bigiel et al. 2016). Consequently, the gas density traced by each molecular line is not fully understood particularly in disk regions. Nonetheless, the gas density in relatively quiescent disk regions is crucial for total understanding of star formation activities in a whole galaxy.
With this in mind, we have conducted very sensitive observations of the lowest transition line of H$_2$CO (1$_{01}$ − 0$_{00}$) toward a position in a spiral arm of the nearby spiral galaxy M51 (D = 8.4 Mpc; Vinkó et al. 2012). In conjunction with the previously observed 2$_{02}$ − 1$_{01}$ line (Watanabe et al. 2014), we evaluate the gas density of the emitting region of H$_2$CO by nonlocal thermal equilibrium (LTE) analyses. The observation of the 1$_{01}$ − 0$_{00}$ is essential to derive the gas density in cold and less dense conditions. In addition, we derive the gas density of the emitting region of CS by using the existing data of the two CS lines (J = 2 − 1 and 3 − 2; Watanabe et al. 2014). Based on the derived quantities, we consider the realistic H$_2$ density distribution within the telescope beam (∼1 kpc). We also present implications of the derived results to formation processes of H$_2$CO and CS.

2. Observations and Results

Observations of the H$_2$CO (1$_{01}$ − 0$_{00}$) line at 72.8379480 GHz were carried out with the 45 m radio telescope at the Nobeyama Radio Observatory (NRO 45 m) in 2014 May. The half power beamwidth is ∼22.5′ at the observing frequency (72.72 GHz). We used the dual-polarization sideband separating (2SB) receiver T70. The system temperature ranged from 180 to 270 K. The sideband separation was typically 10–15 dB or better. The backend was the autocorrelator SAM45 (Kuno et al. 2011; Kamazaki et al. 2012). The frequency resolution and bandwidth are 488.28 kHz and 1600 MHz, respectively. The antenna temperature $T_a$ was corrected for the main-beam efficiency of 0.45 to obtain the main-beam temperature $T_{MB}$.8 We employed the position-switching mode, where the on-source integration time of each scan was set to 20 s. The observed position was M51 P1 ($\alpha$J2000 = 13h29m50s, $\delta$J2000 = +47°11′25″) toward which Watanabe et al. (2014) conducted a spectral line survey in the 3 mm and 2 mm bands using the IRAM 30 m (Figure 1). The position is the brightest 12CO (1 − 0) peak in the spiral arm. It contains H$_2$ and Pao emission spots and is also bright in 24 μm continuum emission, all of which indicate that star formation occurs inside (Schinnerer et al. 2010; Egusa et al. 2011). The off-source position was 10′ away in azimuth from the on-source position. The telescope pointing was checked every 1–1.5 hr by observing nearby SiO maser sources (S-UMi and R-Cvn). The on-source integration time and the total observation time were 18 hr and 50 hr, respectively. The observation data were reduced with the NRO software NEWSTAR. In the analysis, we binned six successive channels of SAM45 to improve the signal-to-noise ratio. The resultant velocity resolution is 12.2 km s$^{-1}$ at 72 GHz. The rms noise temperature was 2 mK in the $T_{MB}$ scale. Then, a baseline of the fifth-order polynomial was subtracted in the velocity range from −200 to 1200 km s$^{-1}$. The line parameters were obtained by a single Gaussian fitting (Figure 2 top left), as summarized in Table 1.

The H$_2$CO (1$_{01}$ − 0$_{00}$) line was also observed with the IRAM 30 m telescope in 2018 January and May, as a part of the 70 GHz band line survey toward the corresponding position in M51 (Watanabe et al. 2019). The observation was conducted by using the dual-sideband dual-polarization EMIR receiver9 and the Fourier transform spectrometers. The half power beamwidth of IRAM 30 m at the frequency of the H$_2$CO (1$_{01}$ − 0$_{00}$) line is 33″. We performed a single Gaussian fitting to the observed line profile (Figure 2 middle left) and obtained the line parameters, as shown in Table 1.

In addition to the newly observed data, we use the existing data of the H$_2$CO (2$_{02}$ − 1$_{01}$) and CS (2 − 1 and 3 − 2) lines observed with IRAM 30 m (Watanabe et al. 2014). For these lines, we employ the line parameters reported by Watanabe et al. (2014).

3. Non-LTE Analyses

3.1. Non-LTE Analyses Using RADEX

In order to derive the gas density, we conduct non-LTE analyses of the observed data. We use the publicly available code RADEX (van der Tak et al. 2007) with collisional rate coefficients of H$_2$CO (Wiesenfeld & Faure 2013) and CS (Lique et al. 2006). RADEX requires five input parameters to calculate the intensities of molecular lines: background temperature, line width, column density of a given species, gas kinetic temperature, and H$_2$ density. We select the H$_2$ density and the column density as adjustable parameters to reproduce the observed integrated intensities.

Prior to the analyses, the intensity of each molecular line is corrected for the beam dilution effect. Beam dilution is caused by the coupling between the source and the telescope beam, as $T_B = ([\theta_s^2 + \theta_b^2]/\theta_b^2)T_{MB}$, where $T_B$ is the source-averaged brightness temperature, $\theta_s$ is the source size, $\theta_b$ is the beam size of the telescope, and $T_{MB}$ is the measured main-beam temperature. For H$_2$CO, the source size is derived to be 25″ (1 kpc) by using the two measurements of the H$_2$CO (1$_{01}$ − 0$_{00}$) line with the different telescope beams (22′′4 and 33′′8). Such a wide distribution seems likely, because H$_2$CO is

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8http://www.nro.nao.ac.jp/~nro45mrt/html/prop/eff/eff2013.html

9http://www.iram.es/IRAMES/mainWiki/EmirforAstronomers
ubiquitously detected toward Galactic clouds (e.g., ~80% of 262 Galactic radio sources; Downes et al. 1980). For CS, we assume the source size on the basis of the interferometric observations in the literature: Watanabe et al. (2016) mapped the same region in the CS \((2-1)\) line with the Combined Array for Research in Millimeter-wave Astronomy (CARMA) at a ~6″ resolution. The CS emission has a distribution extending along the spiral arm with a size of ~20″ (0.8 kpc). The flux resolved out by the interferometer (missing flux) is estimated to be ~30% by comparing with the flux obtained with IRAM 30 m (Watanabe et al. 2014). We should keep in mind that the flux from the extended component may contribute appreciably in the single-dish observations. Hence, we assume the two source sizes of 25″ and 20″ for both H\(_2\)CO and CS in the following analyses.

The assumptions in the analyses are as follows: we adopt the cosmic microwave background temperature of 2.73 K. For the line width, we use 37 km s\(^{-1}\) for H\(_2\)CO and 48 km s\(^{-1}\) for CS, taking an average of the observed values (Table 1). As for the gas kinetic temperature, Schinnerer et al. (2010) derive it to be 16–20 K by a large velocity gradient (LVG) modeling of the line intensity ratios of \(^{12}\)CO \((1-0)\), \(^{12}\)CO \((2-1)\), and \(^{13}\)CO \((1-0)\). Hence, we assume a somewhat wide range of the temperature, i.e., 10, 15, and 20 K. We run the RADEX code with the above parameters, where model grids of the H\(_2\) density and the column density are set to 30 values logarithmically.
The uncertainties of the line ratio $\nu_{101} - \nu_{000}$ and $2\nu_{02} - \nu_{101}$ are 3σ.

### Table 1

| Molecule | Transition | Frequency (GHz) | $E_{up}$ (K) | $\int T_{mb} dv$ (K km s$^{-1}$) | FWHM (km s$^{-1}$) | $v_{LSR}$ (km s$^{-1}$) | $T_{MB}$ peak (mK) | $\theta_{beam}$ (″) | Reference |
|----------|------------|----------------|-------------|--------------------------------|-----------------|---------------------|-----------------|----------------|-----------|
| H$_2$CO  | 1$_{01} - 0_{00}$ | 72.837948 | 3.5 | 0.30 ± 0.09 | 29 ± 19 | 498 ± 3 | 10 ± 6 | 22.4 | This work |
| H$_2$CO  | 2$_{02} - 1_{01}$ | 145.602949 | 10.5 | 0.14 ± 0.03 | 49 ± 17 | 495 ± 7 | 4 ± 1 | 33.8 | Watanabe et al. (2019) |
| CS       | 2 – 1     | 97.980953 | 7.1 | 0.68 ± 0.08 | 52 ± 3 | 497 ± 1 | 13 ± 2 | 25.1 | Watanabe et al. (2014) |
| CS       | 3 – 2     | 146.969029 | 14.1 | 0.4 ± 0.1 | 45 ± 4 | 495 ± 2 | 9 ± 3 | 16.7 | Watanabe et al. (2014) |

**Notes.** The uncertainties are 3σ.

* The half power beamwidth of IRAM 30 m at the given frequency $\nu$ is $2460^\nu \cdot (\nu/\text{GHz})^{-1}$.

### Table 2

Results of RADEX non-LTE Modeling (Single Density Component)

| Molecule | $\theta_{source}$ (″) | $T_{kin}$ (K) | $N_{mol}$ (cm$^{-2}$) | $\tau$ | $n_{H_2}$ (cm$^{-3}$) | Comments |
|----------|-----------------|---------------|-----------------|------|------------------|----------|
| H$_2$CO  | 25              | 10            | $3.3 \times 10^{12}$ | 0.014 | $2.6 \times 10^{4}$ | See Figure 3 |
|          | 15              |               | $5.0 \times 10^{12}$ | 0.024 | $1.1 \times 10^{5}$ |
|          | 20              |               | $7.1 \times 10^{12}$ | 0.038 | $5.7 \times 10^{5}$ |
|          | 10              |               | $9.0 \times 10^{12}$ | 0.048 | $1.1 \times 10^{5}$ |
|          | 15              |               | ...              | ...   | ...              | a        |
|          | 20              |               | ...              | ...   | ...              | a        |
| CS       | 25              | 10            | $8.1 \times 10^{12}$ | 0.014 | $1.2 \times 10^{5}$ | See Figure 3 |
|          | 15              |               | $8.9 \times 10^{12}$ | 0.016 | $6.4 \times 10^{4}$ |
|          | 20              |               | $1.0 \times 10^{12}$ | 0.019 | $4.3 \times 10^{4}$ |
|          | 10              |               | $1.2 \times 10^{13}$ | 0.022 | $9.5 \times 10^{4}$ |
|          | 15              |               | $1.4 \times 10^{13}$ | 0.028 | $4.7 \times 10^{4}$ |
|          | 20              |               | $1.7 \times 10^{13}$ | 0.036 | $2.9 \times 10^{4}$ |

**Notes.** Columns are (1) molecular species, (2) assumed source size, (3) assumed gas kinetic temperature, (4) derived column density, (5) derived optical depth of the 1$_{01} - 0_{00}$ and 2 – 1 lines for H$_2$CO and CS, respectively, (6) derived H$_2$ density of the emitting region, and (7) other remarks.

* The assumed parameter set of the gas kinetic temperature and the source size does not reproduce the observed intensities at any set of the H$_2$ density and the column density.
spaced from $10^2$ to $10^6$ cm$^{-3}$ and 30 values logarithmically spaced from $10^{10}$ to $10^{15}$ cm$^{-2}$, respectively.

As a result, we successfully constrain the H$_2$ densities of the emitting regions and the column densities from the observed integrated intensities and their ratios for some combinations of the assumed parameters. The derived H$_2$ densities and column densities are listed in Table 2. In Table 2, we also report the optical depths for the H$_2$CO ($1_{01} - 0_{00}$) and CS (2 − 1) lines for reference. Figure 3 shows an example of a plausible parameter set. Depending on the gas kinetic temperature (10−20 K) and the source size ($20''−25''$), the H$_2$ density spans from $5.7 \times 10^3$ to $2.6 \times 10^6$ cm$^{-3}$ for H$_2$CO and $2.9 \times 10^3$ to $1.2 \times 10^5$ cm$^{-3}$ for CS. The column densities are in the range of $(3.3−9.0) \times 10^{12}$ cm$^{-2}$ for H$_2$CO$^{10}$ and $(0.8−1.7) \times 10^{13}$ cm$^{-2}$ for CS. Note that the observed intensities for H$_2$CO cannot be reproduced with any set of the H$_2$ density and the column density, if the gas kinetic temperature is assumed to be of 15 and 20 K with the source size of 20$''$.

3.2. The H$_2$ Densities for the Emitting Regions of H$_2$CO and CS

As described in the previous section, the H$_2$ densities for the emitting region of H$_2$CO and CS are evaluated to be $(0.6−2.6) \times 10^4$ cm$^{-3}$ and $(2.9−12) \times 10^4$ cm$^{-3}$, respectively. It seems reasonable that the derived H$_2$ densities for the emitting region of H$_2$CO ($1_{01} - 0_{00}$) and CS (2 − 1) are higher than that derived for $^{13}$CO (1 − 0) and $^{12}$CO (1 − 0, 2 − 1) ($120−240$ cm$^{-3}$; Schinnerer et al. 2010), because the H$_2$CO and CS lines have higher critical densities than the CO isotopologue lines. Indeed, the derived densities are similar to the effective critical densities ($H_2$CO ($1_{01} - 0_{00}$): $3 \times 10^5$ cm$^{-3}$, CS (2 − 1): $5 \times 10^5$ cm$^{-3}$) at 15 K; Shirley (2015).

As expected, the derived density in the spiral arm of M51 is lower than that in the central region of M51 derived by the HCN (1 − 0) and $^{13}$CO (1 − 0) lines (>100 K and ~10$^5$ cm$^{-3}$; Matsushita et al. 1998), where a heavily obscured AGN associated with a radio jet and ionized/molecular outflows exists (e.g., Kohno et al. 1996; Matsushita et al. 2007). This result seems reasonable because the observed position in the spiral arm is, unlike the central region, free from nuclear jets and/or compression by supernova-driven winds.

Although the H$_2$ densities of the emitting region of H$_2$CO and CS are higher than that of CO isotopologues, they seem to be widely distributed over the GMCs. If H$_2$CO and CS are localized to dense clumps and are deficient in diffuse parts of clouds, the derived gas densities would be higher. The similarity of the derived H$_2$ densities and the effective critical densities may imply that H$_2$CO and CS reside in the wide ranges of density from that well below to that well above the effective critical densities. Hence, both H$_2$CO and CS are not localized to dense star-forming cores (<0.1 pc and >10$^5$ cm$^{-3}$), but rather reside in a considerably large fraction of the GMCs. Our result indicates that H$_2$CO and CS in relatively less dense parts of molecular clouds mainly contribute to their emission in the 3 and 2 mm regions. This result should be considered in the interpretation of molecular emissions in a disk region of a galaxy observed with a molecular-cloud-scale beam.

4. Implications for Realistic Density Distributions

Both theoretical and observational studies have pointed out that molecular clouds comprise a wide range of gas densities from diffuse to dense ones. As a functional form of density distribution, lognormal functions are often predicted by turbulent theories (e.g., Padoan & Nordlund 2002). Milky Way observations are basically consistent with these theories, but it is sometimes pointed out that power laws better describe distributions at high densities (e.g., Lombardi et al. 2015). To explore the density distribution from spatially unresolved observations toward external galaxies, Leroy et al. (2017) demonstrated that a proper set of molecular line intensities is useful to probe underlying distributions. Given that H$_2$CO and CS are widely distributed over the molecular clouds, we here consider the H$_2$ density distribution within the observed 1 kpc beam, assuming a lognormal distribution with and without a power-law tail as employed by Leroy et al. (2017).

4.1. Modeling of Line Intensity and Emissivity

Prior to integrating the intensities for a wide range of H$_2$ density, we run the RADEX code to calculate line intensities of the H$_2$CO and CS transitions at each density. As the input parameters for RADEX, we adopt the same values as in Section 3: the background temperature of 2.73 K, the gas kinetic temperature $T_{\text{kin}}$ of 10 and 15 K, and line widths of 37 and 48 km s$^{-1}$ for H$_2$CO and CS, respectively. The H$_2$ densities are 70 values logarithmically spaced in the range of $10^1$ to $10^8$ cm$^{-3}$. Following Leroy et al. (2017), we adjust the molecular column density to keep the optical depth fixed. Based on the estimation in Section 3.1, we set the optical depth of the lower-J transitions to be $\tau = 0.03$ and 0.01. The optical depth of the higher-J transition is calculated consistently from the lower-J transition. Under the fixed optical depth, the column density varies as a function of H$_2$ density (Figure 4). However, the abundance variations of H$_2$CO and CS may be underestimated, because chemical models predict even larger variations along H$_2$ density (e.g., Harada et al. 2019). The abundance variations could be improved by taking chemical processes into account in future work.

For each density step, we calculate emissivity $\epsilon$. Here, emissivity is defined as the intensity $I$ divided by the H$_2$ column density $N_{\text{H}_2}$. For consistency with Leroy et al. (2017), the column density of H$_2$ is calculated by dividing the column density of emitting molecule $N_{\text{mol}}$ by the fractional abundance of the molecule $X_{\text{mol}}$. Then, the emissivity is calculated as $\epsilon = I/N_{\text{mol}}X_{\text{mol}}^{-1}$. The fractional abundance is adjusted to be $10^{-9}$ for both H$_2$CO and CS so that $N_{\text{mol}}X_{\text{mol}}^{-1}$ is roughly comparable with the reported column density of $N_{\text{H}_2} = (2.3−3.3) \times 10^{22}$ cm$^{-2}$ (Schinnerer et al. 2013).
which is determined by the relation $\ln n^\star = -\sigma^2/2$. As the lognormal distribution is a result of isothermal supersonic turbulence, $\sigma$ is related to the turbulent Mach number $M$: $\sigma^2 = \ln(1 + M^2/4)$ (for more details, see Padoan & Nordlund 2002). For easier comparison with Leroy et al. (2017), we use $\log_{10} \sigma$, so that $\sigma$ is represented in dex. To incorporate a power-law tail, we employ the formulation:

$$dP(\ln n') \propto \exp\left(\frac{(\ln n' - \ln n^\star)^2}{2\sigma^2}\right) d\ln n',$$

where $dP$ is the fraction of cells in a logarithmic step $d\ln n'$, $n' = n_{H_2}/n_0$ is the $H_2$ density normalized by the mean $H_2$ density $n_0$, and $\sigma$ is the rms dispersion of the distribution. The distribution peaks at the mean of the logarithm of the density $\ln n^\star$, which is determined by the relation $\ln n^\star = -\sigma^2/2$. As the lognormal distribution is a result of isothermal supersonic turbulence, $\sigma$ is related to the turbulent Mach number $M$: $\sigma^2 = \ln(1 + M^2/4)$ (for more details, see Padoan & Nordlund 2002). For easier comparison with Leroy et al. (2017), we use $\log_{10} \sigma$, so that $\sigma$ is represented in dex. To incorporate a power-law tail, we employ the formulation:

$$dP(\ln n') \propto \exp(\alpha(\ln n' - \ln n^\star)) d\ln n',$$

where the power-law index is taken to be $\alpha = -1.5$, and the threshold for the power-law tail to be $\ln n_{thresh}^\star = 3.8$ (Federrath & Klessen 2013). The model grids of the mean $H_2$ density and the width of distribution are set to be logarithmically spaced 40 points in the range of $n_0 = 10^4$–$10^7$ cm$^{-3}$, and linearly spaced eight points in the range of $\sigma = 0.4$–$1.2$, respectively, for each of the lognormal distributions with and without power-law tails.

4.3. Realistic $H_2$ Density Distributions

For each $H_2$ density distribution, we derive the beam averaged emissivity by summing up the emissivity along the axis of $H_2$ density (Leroy et al. 2017):

$$\langle \epsilon \rangle = \frac{\int n_{H_2} P(n_{H_2}) \epsilon(n_{H_2}, T_{\text{kin}}, \tau) d n_{H_2}}{\int n_{H_2} P(n_{H_2}) d n_{H_2}}.$$

We calculate the line intensities integrated over the 1 kpc beam, by multiplying the $H_2$ column density of $N_{H_2} = 3 \times 10^{22}$ cm$^{-2}$ (Schinnerer et al. 2013) to the beam averaged emissivity $\langle \epsilon \rangle$.

This causes a minor inconsistency between $N_{H_2}$ and $N_{\text{mol}}X_{\text{mol}}^{-1}$, because $N_{\text{mol}}X_{\text{mol}}^{-1}$ slightly vary within the model distribution. As we do not know the exact fractional abundances of molecules at a specific $H_2$ density, we employ the simplest assumption.

By comparing the modeled line intensities and their ratios with observed ones, the parameters of the density distribution are constrained as summarized in Table 3. In Figure 5, we show the model grids for plausible parameter sets. Figure 6 illustrates the distribution of volume, mass, emissivity, and emission for each plausible parameter set. Compared with pure lognormal distributions, the model with a power-law tail tends to show the lower mean $H_2$ density and the narrower width of distribution. The mean $H_2$ density is in the range of $n_0 = 130$–$6600$ cm$^{-3}$. This seems reasonable, because the range overlaps to $120$–$240$ cm$^{-3}$, which is derived from $^{13}$CO and $^{12}$CO observations (Schinnerer et al. 2013). The width of distribution, on the other hand, is in the range of $\sigma = 0.4$–$0.9$, which corresponds to $M = 2.3$–$18$ in turbulent Mach number. This range almost falls on the smallest case of the typical value (5–100) for spiral and starburst galaxies (Leroy et al. 2016).

Note that, in any density distribution, we cannot simultaneously reproduce the observed intensity of $H_2CO$ and CS. This would probably originate from the fixed kinetic temperature and, most notably, the arbitrary assumption for their abundances to keep the optical depth fixed. In the next section, we discuss chemical processes to form $H_2CO$ and CS, which may differentiate their distribution. Implementing more realistic molecular abundance variation is awaited for future study.

Finally, we discuss the median intensity for emission $I_{\text{med}}$, which is defined by the $H_2$ density below which 50% of the line emission emerges (Leroy et al. 2017). Here, we consider the lines of lower-$J$ transitions, i.e., $J_{01} - J_{00}$ for $H_2CO$ and $2 - 1$ for CS. The modeled values of the median intensity for emission are shown in Table 3. These are consistent with the $H_2$ densities of the emitting regions derived in Section 3. This supports the picture suggested in Section 3.2 that $H_2CO$ and CS are present in a wide range of $H_2$ density.

5. Implications for Chemical Processes

Formation and destruction processes of molecules depend on the physical conditions. The relatively low density ($\sim 10^4$ cm$^{-3}$) of the emitting regions of $H_2CO$ and CS suggests that these molecules are not localized to dense and hot regions associated with active star formation. In the following subsections, implications of this result to the chemical processes of $H_2CO$ and CS are discussed.

5.1. $H_2CO$

In general, both grain-surface reactions and gas-phase reactions are thought to contribute to the production of $H_2CO$. Theoretical models and laboratory experiments suggest that successive hydrogenation of CO in icy mantles of dust grains followed by subsequent liberation into the gas phase by thermal and/or nonthermal desorption is the dominant process (CO $\rightarrow$ HCO $\rightarrow$ H$_2$CO; Watanabe & Kouchi 2002), although the gas-phase formation can produce some abundance of H$_2$CO (e.g., Soma et al. 2018).

In our case, widespread $H_2CO$ in relatively less dense gas would not originate from thermal desorption. As the desorption
temperature is as high as 40 K, the thermal desorption is restricted in small hot and dense regions around newly born stars (i.e., hot cores) and/or outflow shocked regions. Then, the nonthermal desorption should mainly be responsible for the liberation of H$_2$CO formed in ice mantles. This is supported by the previous observation of CH$_3$OH toward this position of M51 (Watanabe et al. 2014, 2016). According to them, the distribution of CH$_3$OH is widespread over a 100 pc scale. CH$_3$OH is formed on grain surface by further hydrogenation of H$_2$CO (H$_2$CO $\rightarrow$ CH$_3$O $\rightarrow$ CH$_3$OH; Watanabe & Kouchi 2002), whereas it is not efficiently produced by the gas-phase reactions (Geppert et al. 2006). Therefore, a widespread CH$_3$OH suggests its nonthermal desorption, and in this case, H$_2$CO should also be liberated. As for the nonthermal desorption processes, sputtering of molecules in large-scale shocks such as spiral shocks and cloud–cloud collisions as well as temporal heating of dust grains by cosmic rays and liberation assisted by a surplus of reaction energy in the formation of molecules are proposed (e.g., Hasegawa & Herbst 1993; Garrod et al. 2007). It is worth noting that desorption by UV photons can also work for H$_2$CO but not for CH$_3$OH (Martin-Doménech et al. 2016).

The abundance ratio CH$_3$OH/H$_2$CO in M51 P1 is evaluated to be 1.5 by using the column density of H$_2$CO obtained in this study and that of CH$_3$OH reported by Watanabe et al. (2014). Here, the ortho-to-para ratio of H$_2$CO is assumed to be the statistical value of 3, and the line intensity of CH$_3$OH is corrected for the source size of 25" for the fair comparison. The CH$_3$OH/H$_2$CO ratio in various Galactic objects varies by two orders of magnitude from 0.3 (e.g., Oph A D-peak; Bergman et al. 2011) to 24 (e.g., NGC 6334 IRS1; van der Tak et al. 2000). The difference may originate from different hydrogenation of CO in ice mantles and/or different contribution of the gas-phase production. The ratio in M51 P1 is just in the middle of this range. It is not very different from those in the other external galaxies M82 (1.1; Aladro et al. 2011a) and NGC 253
5.2. CS

It is well known that CS is ubiquitous in various interstellar sources including diffuse clouds (e.g., Lucas & Liszt 2002). Gas-phase reactions are thought to be important in its production, and hence, CS can be formed under the less dense condition of M51 P1. According to the interferometric observation by Watanabe et al. (2016), the distribution of CS is slightly more extended than CH$_3$OH in M51 P1. Hence, the different spatial distribution would originate from the contribution of the gas-phase production of CS as oppose to the grain-surface production of CH$_3$OH. The slightly different H$_2$ densities derived from H$_2$CO and CS would suggest the different production mechanism.

The CS/H$_2$CO ratio is evaluated to be 0.5 in M51 P1. The ratios in various Galactic sources range from 0.4 (e.g., Galactic diffuse clouds; Liszt et al. 2006) to 1.6 (e.g., IRAS 16293-2422; Blake et al. 1994; van Dishoeck et al. 1995), and hence, the ratio in M51 P1 falls in this range. It is worth noting that the ratios are 1.8 in M82 (Aladro et al. 2011a) and 1.6 (180 km s$^{-1}$ component)—2.9 (285 km s$^{-1}$ component) in NGC 253 (Martín et al. 2006), which also agree with the ratio in M51 P1 by a factor of a few, as in the case for the CH$_3$OH/H$_2$CO ratio. We need more samples to examine whether this is just by chance or by some chemical reasons.

These results provide us with additional support that the molecular composition averaged over a few 10–100 pc scale observed with single-dish telescopes in the 3 mm wavelength range mostly reflects that of the widespread gas rather than that affected by local star formation activities, as inferred by the previous studies of Galactic GMCs (Nishimura et al. 2017; Watanabe et al. 2017). According to them, the 3 mm band spectra averaged over a GMC scale (the 39 pc $\times$ 47 pc area in W51; Watanabe et al. 2017 and the 9 pc $\times$ 9 pc area in W3(OH); Nishimura et al. 2017) are similar to the spectra of...
diffuse cloud peripheries rather than those of dense regions. This trend is also supported by the chemical model calculation by Harada et al. (2019).

6. Summary

We study the gas densities of the emitting regions of the two commonly observed molecular species H$_2$CO and CS in a 1 kpc region in the spiral arm of M51. We have conducted sensitive observations of the H$_2$CO (101−000) line using the NRO 45 m and IRAM 30 m telescopes. Combining our new data with the data of H$_2$CO (202−101) and CS (3−2) previously reported by Watanabe et al. (2014), we find that the emitting regions of H$_2$CO and CS have the relatively low H$_2$ densities of (0.6–2.6) × 10$^4$ cm$^{-3}$ and (2.9–12) × 10$^4$ cm$^{-3}$, respectively. This indicates that these two species are not concentrated in the star-forming cores, but are widely distributed over the GMCs. Models assuming the lognormal H$_2$ density distribution with fixed optical depths also support this picture. The different H$_2$ densities derived for H$_2$CO and CS imply their different distributions, and probably different formation processes.

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Facility: NRO 45 m. 
Software: Newstar.

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