SPECTRAL LINE SURVEY TOWARD A MOLECULAR CLOUD IN IC10

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ABSTRACT

We have conducted a spectral line survey observation in the 3 mm band toward the low-metallicity dwarf galaxy IC10 with the 45 m radio telescope of the Nobeyama Radio Observatory to explore its chemical composition at a molecular-cloud scale (~80 pc). The CS, SO, CCH, HCN, HCO+, and HNC lines are detected for the first time in this galaxy in addition to the CO and 13CO lines, while the c-C3H2, CH3OH, CN, C18O, and N2H+ lines are not detected. The spectral intensity pattern is found to be similar to those observed toward molecular clouds in the Large Magellanic Cloud (LMC), whose metallicity is as low as IC10. Nitrogen-bearing species are deficient in comparison with the Galactic molecular clouds due to a lower elemental abundance of nitrogen. CCH is abundant in comparison with Galactic translucent clouds, whereas CH3OH may be deficient. These characteristic trends for CCH and CH3OH are also seen in the LMC, and seem to originate from photodissociation regions more extended in the peripheries of molecular clouds due to the lower metallicity condition.

Key words: galaxies: individual (IC10) – galaxies: ISM – ISM: molecules

1. INTRODUCTION

The Local Group of galaxies comprises 50 or more galaxies, a majority of which are low-metallicity dwarf galaxies. Observations of such low-metallicity galaxies provide us with clues for understanding the chemical characteristics of distant galaxies in the early universe, which are in a metal-poor environment. It is generally thought that metallicity has a strong impact on the chemical composition of molecular clouds (e.g., van Dishoeck & Black 1988; Millar & Herbst 1990). In a metal-poor environment, not only are metal-bearing species less abundant, but the production and destruction processes of molecules are expected to be different from those in a metal-rich environment. For example, photodissociation and photoionization are more effective in molecular clouds in low-metallicity conditions owing to the lower abundance of dust grains (e.g., Millar & Herbst 1990). Thus, detailed characterization of the chemical features in low-metallicity galaxies is of fundamental importance in astrochemistry and astrophysics.

However, radio-astronomical observational studies on the chemical composition of low-metallicity galaxies have so far been very sparse. Molecular line emission from low-metallicity galaxies is generally faint, and hence observations have almost been limited to CO and its isotopologues. A notable exception is the Large Magellanic Cloud (LMC). Because of its proximity to the Sun (d ~ 49.97 ± 1.11 kpc Pietrzyński et al. 2013), molecular line observations are carried out toward active star-forming regions (e.g., Chin et al. 1997; Heikkilä et al. 1999; Wang et al. 2009; Paron et al. 2014). Thanks to the recent improvements of observing instruments, spectral lines of less abundant species are now observable in external galaxies with a reasonable observation time, which enable us to study their chemical compositions (e.g., Martín et al. 2006; Aladro et al. 2013; Watanabe et al. 2014). Such a situation is also true even for low-metallicity galaxies.

We recently conducted spectral line observations of molecular clouds in the LMC with the Mopra 22 m telescope as the initial step to characterize molecular-cloud-scale chemical composition characteristic to a low-metallicity condition (Nishimura et al. 2016). We observed seven molecular clouds that have different star-formation activities; two are quiescent molecular clouds which are not associated with infrared counterparts detected with AKARI or Spitzer, three are molecular clouds associated with high-mass star formation, and two are active star-forming clouds with the extended H II region. The difference of star-formation activities is reflected in infrared fluxes; their 8 µm fluxes vary from 26.8 to 946.8 mJy arcsec−2 (38 arcsec beam averaged, Spitzer/IRAC; Meixner et al. 2006). We found that the chemical compositions of the seven sources are similar to each other regardless of the large difference of star-formation activities. Since the beam size of the Mopra corresponds to the spatial resolution of 10 pc at the LMC distance, the major contribution to the observed spectra is rather diffuse molecular gas extending over the molecular clouds. The contribution from the star-forming cores seems to be smeared out in the observations. In other words, the observed chemical composition is characteristic of molecular clouds in the LMC.

By comparing the results with those observed in a metal-rich environment such as our Galaxy and the spiral arm of M51, the following two characteristics of the LMC spectra are found (Nishimura et al. 2016). (1) Nitrogen-bearing species (HCN, HNC, N2H+, HNCO, CN) are obviously faint in the LMC, which originates from the low elemental abundance of nitrogen. (2) The lines of CCH are relatively brighter and the lines of CH3OH are much weaker in the LMC than those in the spiral arm of M51. Moreover, the CH3OH/HCO+ ratios in the LMC are higher than those found in the nearby translucent clouds in our Galaxy. This trend would originate from the...
stronger UV radiation field owing to the lower abundance of dust grains.

We expect that the characteristics of the LMC can generally be found in other low-metallicity galaxies. To examine this prediction, we observed another low-metallicity galaxy, IC10. IC10 is located at a distance of ~950 kpc (Hunter 2001), and its metallicity is lower by a factor 5 than in the Solar neighborhood (Garnett 1990). The star-formation rate estimated from Hα (0.2 M⊙ yr⁻¹; Gil de Paz et al. 2003) and the association of the large number of Wolf–Rayet stars (~100; Massey & Holmes 2002) imply active star formation in IC10. IC10 has been studied in C II (158 μm; Madden et al. 1997), C I (P1 − 3P1; Bolatto et al. 2000), and multi-transitions of CO (e.g., Petipas & Wilson 1998; Bolatto et al. 2000; Leroy et al. 2006). However, with the exception of CO and its isotopologues, molecular line observations have not been reported.

2. OBSERVATIONS

The observations were carried out with the 45 m radio telescope at the Nobeyama Radio Observatory (NRO) in February and March 2015. We observed most of the frequency range from 84 to 116 GHz. We did not observe the frequency range of 91–91.5, 95.5–96, 100–103.5, and 107.5–108 GHz because no spectral lines were detected in the LMC sources (Nishimura et al. 2016). The half-power beam width (HPBW) of the telescope is 20°4, 16°6, and 15°3 at 86, 110, and 115 GHz, respectively. They correspond to the spatial scale of 71.7 to 98.8 pc at the IC10 distance (d = 950 kpc). The telescope pointing was checked by observing a nearby SiO maser source (Y Cas) every hour, and the pointing accuracy was maintained to be better than 5″.

We observed two orthogonal polarization signals simultaneously by using the SIS mixer receiver (TZ1), whose system temperatures ranged from 120 to 280 K. The backend is the autocorrelator SAM45. The frequency resolution and bandwidth are 488.24 kHz and 1600 MHz, respectively. We binned two successive channels of SAM45 in the analysis to improve the signal-to-noise ratio. The resultant velocity resolution is 3.25 km s⁻¹ at 90 GHz. The line intensity was calibrated by the chopper wheel method, and a typical calibration accuracy is 20%. The antenna temperature is divided by the main beam efficiency of 0.49 at 86 GHz, 0.42 at 100 GHz, and 0.40 at 115 GHz to obtain the main beam temperature TMB. We employed the position-switching mode, where the on-source integration time of each scan was set to be 20 s for all of the observations. The observed position is αJ2000 = 00°12'27"09, δJ2000 = 59°17'01"00, where the 12CO (J = 1 − 0) line intensity is the strongest in IC10, according to Leroy et al. (2006). The position is also confirmed to be bright in infrared (JHK, Spitzer/IRAC, and Spitzer/MIPS; Lebouteiller et al. 2012). The off-source position is 3° away in azimuth from the on-source position. The total observation time was 55 hr (~18 hr for on-source). A typical rms noise temperature for each line in the TMB scale is 2.5–8.0 mK for 84–112 GHz and 31–53 mK for 112–116 GHz at a frequency resolution of 976.5 kHz.

3. RESULTS

Figure 1 shows the observed spectrum in the frequency range from 84 to 100 GHz, which is a part of the total observed spectrum. We detected the lines of CCH(N = 1 − 0), HCN (J = 1 − 0), HCO⁺(J = 1 − 0), HNC(J = 1 − 0; tentative detection), CS(J = 2 − 1), and SO(NJ = 2−1) in this frequency range for the first time. In addition, we also detected the lines of 13CO(J = 1 − 0) and 12CO(J = 1 − 0). On the other hand, the lines of c-C3H2(212−101), N2H+(J = 1 − 0), CH3OH(J0 = 20 − 10, A′), 18O(J = 1 − 0), and CN(N = 1 − 0) were not detected (Figure 2). Surprisingly, the spectral intensity pattern is very similar to that of the molecular cloud N44C in the LMC, although the molecular line intensities are weaker by a factor of about one-sixth than that toward N44C. Figure 3 (left) shows the integrated intensities of IC10 versus those of the LMC cloud N44C. Indeed, a good correlation is seen between the two sources. The correlation coefficient is as high as 0.96. Even if the 13CO data are excluded, it is 0.90. On the other hand, the spectrum toward IC10 significantly differs from that observed in the spiral arm of M51. This is also confirmed by the rather poor correlation in Figure 3 (right). The correlation coefficient is 0.83, while it is as low as 0.18 without 13CO. As mentioned in Section 1, the spectrum of N44C reflects the GMC-scale chemical composition characteristic to the LMC, and hence the similarity seems to originate from the low-metallicity environment of IC10.

The line parameters derived by Gaussian fitting are summarized in Table 1. The velocity of the peak of the 12CO line (−330.2 km s⁻¹) is consistent with the previous observation of the 12CO (J = 1 − 0) line toward the same position with the Arizona Radio Observatory 12 m telescope (HPBW of 50°) by Leroy et al. (2006) (−330.5 km s⁻¹). The integrated intensity of 12CO observed by Leroy et al. (2006) is lower than ours only by a factor of 1.3, in spite of a large difference of the telescope beam size (15°3 and 55°5). This result indicates that the 12CO emitting region is at least extended over the beam size of the Nobeyama 45 m telescope. The vLSR values of the detected lines range from −326 to −333 km s⁻¹, which is consistent with that of the 12CO line. The line widths are mostly in the range from 12 to 16 km s⁻¹. Exceptions are the HNC line and one of the CCH lines probably due to a poor signal-to-noise ratio (3.8σ) and the blending of nearby hyperfine components, respectively (Figure 2).

We evaluated beam-averaged column densities by statistical equilibrium calculations, as we did for the LMC clouds (Nishimura et al. 2016). We employed the RADEX code (van der Tak et al. 2007) for this purpose. Since only one rotational transition was observed for each molecular species, we assumed a range of the gas kinetic temperature to be from 10 to 50 K, and a range of the H2 density from 3 × 10³ to 1 × 10⁶ cm⁻³. Although the H2 density of 3 × 10³ and 10⁶ cm⁻³ seem too high for the H2 density averaged over the 80 pc scale of molecular clouds, we assumed a wide range of physical conditions for a robust estimate. The beam-averaged column densities are derived for the gas kinetic temperatures of 10, 20, 30, 40, and 50 K and the H2 density of 3 × 10³, 1 × 10⁴, 3 × 10⁴, 1 × 10⁵, 3 × 10⁵, and 1 × 10⁶ cm⁻³, as listed in Table 2.

4. DISCUSSION

4.1. Effect of Elemental Abundances

Elemental abundances are different from galaxy to galaxy, reflecting the past history of star formation. In the low-metallicity galaxies, heavy elements are generally deficient, and in particular the deficiency of nitrogen is most significant.
among the abundant second-row elements (C, N, O; Vincenzo et al. 2016). Because of this, one of the characteristic features in the chemical compositions would be the deficiency of the N-bearing molecules. The chemical model by Millar & Herbst (1990) indeed predicted that abundances of N-bearing species are sensitive to the elemental abundance of nitrogen. The deficiency of the N-bearing molecules is already evident in the spectral pattern of IC10 in comparison with that of the spiral arm of M51. We calculated the abundance ratios of HCN/HCO\(^+\) and HNC/HCO\(^+\) for IC10 under the assumption of an H\(_2\) density of \(3 \times 10^3\), \(1 \times 10^4\), \(3 \times 10^4\), and \(1 \times 10^5\) cm\(^{-3}\), \(3 \times 10^5\), and \(1 \times 10^6\) cm\(^{-3}\), and a gas kinetic temperature of 10, 20, 30, 40, and 50 K, and compared them with the average ratios reported for the seven clouds in the LMC (Nishimura et al. 2016), the average ratios for three translucent clouds (CB17, CB24, CB228) in our Galaxy (Turner 1995b; Turner et al. 1997), and the ratio for the spiral arm position (P1) of M51 observed by Watanabe et al. (2014), as shown in Table 3. The observed spectrum of IC10 are averaged over molecular clouds (\(\sim 80\) pc scale), and seems to be dominated by the
Figure 3. Correlation diagrams of integrated intensities of detected species between IC10 and LMC (N44C; Nishimura et al. 2016, left), and between IC10 and M51 (Watanabe et al. 2014; right). The dashed line indicates the average ratio of the integrated intensities between the two sources.

Table 1
IC10 Observed Line Parameters

| Molecule | Frequency (GHz) | Transition | $T_{mb}$ Peak (mK) | $v_{LSR}$ (km s$^{-1}$) | $\Delta v$ (km s$^{-1}$) | $\int T_{mb} dv$ (K km s$^{-1}$) |
|----------|-----------------|------------|---------------------|-------------------------|--------------------------|---------------------------------|
| c-C$_2$H$_2$ | 85.338894 | $2_{22} - 1_{11}$ | 1.5 | 20 ± 2 | −328.9 ± 0.6 | 15.5 ± 1.4 | 0.329 ± 0.015 |
| CCH | 87.284105 | $N = 1 - 0, J = 5/2 - 3/2, F = 1 - 1$ | 1.5 | 15.5 | 0.329 ± 0.015 |
| CCH | 87.316898 | $N = 1 - 0, J = 5/2 - 3/2, F = 2 - 1$ | 1.5 | 0.329 ± 0.015 |
| CCH | 87.328585 | $N = 1 - 0, J = 5/2 - 3/2, F = 1 - 0$ | 1.5 | 0.311 ± 0.014 |
| CCH | 87.401989 | $N = 1 - 0, J = 3/2 - 1/2, F = 1 - 1$ | 1.5 | 0.28 ± 0.03 |
| CCH | 87.407165 | $N = 1 - 0, J = 3/2 - 1/2, F = 0 - 1$ | 1.5 | 0.28 ± 0.03 |
| CCH | 87.446470 | $N = 1 - 0, J = 3/2 - 1/2, F = 1 - 0$ | 1.5 | 0.28 ± 0.03 |
| HCN | 88.631602 | 1 − 0 | 1.5 | 19 ± 2 | −329.8 ± 0.8 | 15.2 ± 0.3 | 0.337 ± 0.014 |
| HCO$^+$ | 89.188525 | 1 − 0 | 1.5 | 49 ± 2 | −328.9 ± 0.3 | 13.9 ± 0.8 | 0.840 ± 0.013 |
| HNC | 90.665368 | 1 − 0 | 1.5 | 10 ± 3 | −326.7 ± 1.2 | 9 ± 3 | 0.107 ± 0.012 |
| N$_2$H$^+$ | 93.173392 | 1 − 0 | 1.5 | 0.11 |
| CH$_3$OH | 96.741375 | 2$_0$ − 1$_0$, A$^+$ | 1.5 | 30.7 ± 1.6 | −329.2 ± 0.4 | 15.0 ± 0.9 | 0.499 ± 0.011 |
| CS | 97.980953 | 2 − 1 | 1.5 | 14 ± 3 | −331.2 ± 1.7 | 18 ± 4 | 0.28 ± 0.03 |
| SO | 99.299870 | $N_s = 2_3 - 1_2$ | 1.5 | 11 ± 3 | −329.4 ± 0.3 | 12.0 ± 0.6 | 1.51 ± 0.03 |
| C$^{18}$O | 109.782173 | 1 − 0 | 1.5 | 0.6 |
| $^{13}$CO | 110.201354 | 1 − 0 | 1.5 | 0.6 |
| CN | 113.490970 | $N = 1 - 0, J = 3/2 - 1/2, F = 5/2 - 3/2$ | 1.5 | 0.6 |
| $^{12}$CO | 115.271202 | 1 − 0 | 1.5 | 0.6 |

Note. The errors are 1σ. The upper limits are 3σ. The calibration error (∼20%) is not included.

diffuse part of the molecular clouds rather than dense star-forming cores. This is true even for smaller scale observations (∼10 pc scale) of the LMC clouds (Nishimura et al. 2016). Hence, for a fair comparison, we chose the translucent clouds as representatives of our Galaxy. Although the column densities are sensitive to the assumed H$_2$ density and the assumed gas kinetic temperature, the column density ratios for IC10 are affected only less than ±50% in the parameter range. This fact is also shown in the analyses of the LMC spectra (Nishimura et al. 2016). The elemental N/O ratio in IC10 is lower by a factor of 3 than that in our Galaxy (Lequeux et al. 1979). The HCN/HCO$^+$ and HNC/HCO$^+$ ratios in IC10 are comparable to those for the LMC clouds, and are indeed found to be lower than in the three Galactic translucent clouds (CB17, CB24, CB228). Although the HCN/HCO$^+$ ratios of IC10 and the Galactic translucent clouds marginally overlap with each other within the mutual error ranges, the overlap occurs only for specific conditions that are not very likely (3 × 10$^3$ cm$^{-3}$ and 10 K for IC10 and 1 × 10$^5$ cm$^{-3}$ and 50 K for the Galactic translucent clouds). Hence, we can state the above conclusion in spite of the formal error ranges. A similar comparison can also be made for M51 P1, which has a higher N/O ratio than the Solar neighborhood by a factor of 2 (Bresolin et al. 2004). The HCN/HCO$^+$ and HNC/HCO$^+$ ratios in M51 P1 are 8.4$^{+4.0}_{-2.6}$ and 1.6$^{+0.6}_{-0.4}$, respectively, which are higher than those in IC10 (1.9$^{+2.0}_{-1.5}$ and 0.4$^{+0.2}_{-0.2}$, respectively).
| molecule     | \( n_{\text{H}_2} T_e \) | 10 K | 20 K | 30 K | 40 K | 50 K |
|--------------|-----------------|------|------|------|------|------|
| \( c\text{-C}_2\text{H}_2 \) (ortho) | \(<7.9>(+12)\)  | <3.3(+12) | <2.1(+12) | <1.8(+12) | <1.7(+12) | <1.7(+12) |
| CCH          | 7.8(+13)        | 4.1(+13) | 3.2(+13) | 2.8(+13) | 2.5(+13) | 2.5(+13) |
| HCN          | 1.4(+13)        | 8.2(+12) | 6.4(+12) | 5.5(+12) | 4.9(+12) | 4.9(+12) |
| HCO⁺         | 4.3(+12)        | 2.7(+12) | 2.2(+12) | 1.9(+12) | 1.8(+12) | 1.8(+12) |
| HNC          | 1.8(+12)        | 1.3(+12) | 1.1(+12) | 1.0(+12) | 0.9(+11) | 0.9(+11) |
| \( N_2\text{H}^+ \) | <6.0(+11) | <3.8(+11) | <3.2(+11) | <2.8(+11) | <2.6(+11) | <2.6(+11) |
| \( CH_3\text{OH} \) (A) | <3.5(+12) | <2.3(+12) | <2.0(+12) | <1.9(+12) | <1.8(+12) | <1.8(+12) |
| CS           | 2.0(+13)        | 1.2(+13) | 9.5(+12) | 8.2(+12) | 7.4(+12) | 7.4(+12) |
| SO           | 1.9(+13)        | 9.4(+12) | 7.2(+12) | 6.3(+12) | 5.7(+12) | 5.7(+12) |
| \( C^3\text{O} \) | <8.6(+13) | <9.6(+13) | <1.1(+14) | <1.3(+14) | <1.4(+14) | <1.4(+14) |
| \( ^{13}\text{CO} \) | 1.3(+15) | 1.5(+15) | 1.7(+15) | 1.9(+15) | 2.1(+15) | 2.1(+15) |
| CN           | <1.3(+14)       | <6.0(+13) | <3.4(+13) | <2.9(+13) | <2.9(+13) | <2.9(+13) |
| \( ^{12}\text{CO} \) | 8.9(+15) | 9.4(+15) | 1.1(+16) | 1.2(+16) | 1.5(+16) | 1.5(+16) |

| molecule     | \( n_{\text{H}_2} T_e \) | 10 K | 20 K | 30 K | 40 K | 50 K |
|--------------|-----------------|------|------|------|------|------|
| \( c\text{-C}_2\text{H}_2 \) (ortho) | \(<2.8>(+12)\)  | <1.3(+12) | <8.7(+11) | <7.6(+11) | <7.3(+11) | <7.3(+11) |
| CCH          | 3.4(+13)        | 2.1(+13) | 1.8(+13) | 1.6(+13) | 1.6(+13) | 1.6(+13) |
| HCN          | 4.9(+12)        | 2.8(+12) | 2.3(+12) | 2.0(+12) | 1.8(+12) | 1.8(+12) |
| HCO⁺         | 1.7(+12)        | 1.2(+12) | 1.0(+12) | 0.9(+11) | 0.8(+11) | 0.8(+11) |
| HNC          | 6.9(+11)        | 4.9(+11) | 4.3(+11) | 4.1(+11) | 3.9(+11) | 3.9(+11) |
| \( N_2\text{H}^+ \) | <2.6(+11) | <1.8(+11) | <1.5(+11) | <1.4(+11) | <1.4(+11) | <1.4(+11) |
| \( CH_3\text{OH} \) (A) | <2.2(+12) | <1.7(+12) | <1.7(+12) | <1.7(+12) | <1.8(+12) | <1.8(+12) |
| CS           | 7.5(+12)        | 4.7(+12) | 3.9(+12) | 3.5(+12) | 3.2(+12) | 3.2(+12) |
| SO           | 7.4(+12)        | 4.2(+12) | 3.5(+12) | 3.2(+12) | 3.1(+12) | 3.1(+12) |
| \( C^3\text{O} \) | <9.3(+13) | <1.2(+14) | <1.4(+14) | <1.7(+14) | <1.9(+14) | <1.9(+14) |
| \( ^{13}\text{CO} \) | 1.4(+15) | 1.7(+15) | 2.1(+15) | 2.5(+15) | 2.9(+15) | 2.9(+15) |
| CN           | <4.1(+13)       | <2.1(+13) | <1.5(+13) | <1.3(+13) | <1.1(+13) | <1.1(+13) |
| \( ^{12}\text{CO} \) | 9.5(+15) | 1.1(+16) | 1.4(+16) | 1.6(+16) | 1.8(+16) | 1.8(+16) |

| molecule     | \( n_{\text{H}_2} T_e \) | 10 K | 20 K | 30 K | 40 K | 50 K |
|--------------|-----------------|------|------|------|------|------|
| \( c\text{-C}_2\text{H}_2 \) (ortho) | \(<1.0>(+12)\)  | <5.6(+11) | <4.7(+11) | <4.5(+11) | <4.4(+11) | <4.4(+11) |
| CCH          | 1.9(+13)        | 1.5(+13) | 1.5(+13) | 1.5(+13) | 1.6(+13) | 1.6(+13) |
| HCN          | 1.7(+12)        | 1.0(+12) | 8.7(+11) | 7.8(+11) | 7.2(+11) | 7.2(+11) |
| HCO⁺         | 8.9(+11)        | 6.9(+11) | 6.5(+11) | 6.3(+11) | 6.3(+11) | 6.3(+11) |
| HNC          | 2.9(+11)        | 2.2(+11) | 2.0(+11) | 1.9(+11) | 1.8(+11) | 1.8(+11) |
| \( N_2\text{H}^+ \) | <1.4(+11) | <1.1(+11) | <1.0(+11) | <1.0(+11) | <1.0(+11) | <1.0(+11) |
| \( CH_3\text{OH} \) (A) | <1.9(+12) | <1.9(+12) | <2.1(+12) | <2.3(+12) | <2.5(+12) | <2.5(+12) |
| CS           | 3.3(+12)        | 2.3(+12) | 2.1(+12) | 2.0(+12) | 1.9(+12) | 1.9(+12) |
| SO           | 3.8(+12)        | 2.8(+12) | 2.7(+12) | 2.7(+12) | 2.8(+12) | 2.8(+12) |
| \( C^3\text{O} \) | <9.7(+13) | <1.3(+14) | <1.6(+14) | <2.0(+14) | <2.3(+14) | <2.3(+14) |
| \( ^{13}\text{CO} \) | 1.5(+15) | 1.9(+15) | 2.5(+15) | 3.0(+15) | 3.5(+15) | 3.5(+15) |
| CN           | <1.4(+13)       | <7.9(+12) | <6.2(+12) | <5.4(+12) | <4.9(+12) | <4.9(+12) |
| \( ^{12}\text{CO} \) | 9.9(+15) | 1.2(+16) | 1.6(+16) | 1.9(+16) | 2.2(+16) | 2.2(+16) |
Hence, it is most likely that the deficiency of the N-bearing molecules directly reflects the elemental deficiency of nitrogen in the IC10.

The HCN/HCO$^+$ ratio has been discussed for nuclear regions of external galaxies. The HCN/HCO$^+$ ratio is known to be higher for active galactic nuclei (AGNs), which is interpreted as the effect of XDRs, cosmic-rays, and/or shock heatings (e.g., Lepp & Dalgarno 1996; Kohno et al. 2001; Meijerink et al. 2007; Aladro et al. 2015). In this study, we observed GMCs without such effects, and found the lower HCN/HCO$^+$ ratio than the Galactic translucent clouds. Hence, the various effects suggested for AGNs cannot be applied to IC10. Rather, the intrinsic effect of the elemental abundance can be seen in this source.

The CS/SO ratio in IC10 is 0.9$^{+0.9}_{-0.5}$, which is comparable to that of the LMC (1.8$^{+0.8}_{-0.5}$). The ratio is also comparable to that in the Galactic translucent clouds (1.0$^{+0.5}_{-0.4}$), but is lower than that of MS1 P1 (4.6$^{+1.2}_{-1.8}$). Any significant trend due to the difference of the C/O ratio is not seen in the CS/SO ratio in this study.

4.2. Effect of Photodissociation

We calculated the abundance ratio of CCH/HCO$^+$ in the same way as HCN/HCO$^+$ and HNC/HCO$^+$. The ratio of CCH/HCO$^+$ is higher in IC10 (20.9$^{+10.7}_{-9.2}$) than in the Galactic translucent clouds (5.3$^{+3.9}_{-2.4}$) by a factor of 4. This enhancement of CCH in IC10 cannot be interpreted as the effect of elemental abundances. Indeed, the elemental C/O ratio is estimated to be 0.3 in IC10 (Lequeux et al. 1979; Bolatto et al. 2000), while it is 0.6 in the Solar neighborhood. When the low C/O ratio is taken into account, the high CCH/HCO$^+$ ratio in IC10 is striking. This enhancement of CCH is also seen in the LMC clouds (Nishimura et al. 2016).

The effect of photodissociation would be responsible for the enhancement. It is generally thought that CCH is abundant in the photodissociation region (PDR) illuminated by UV radiation (e.g., Pety et al. 2005; Martín et al. 2014; Ginard et al. 2015). In low-metallicity galaxies, the extinction of the UV radiation by dust grains is expected to be less effective for a given column density of H$_2$ because of the lower abundance of dust grains. The PDR would be extended deeper into molecular clouds, which would be responsible to the relatively high abundance of CCH. In the PDR, the growth of large carbon-chain molecules containing more than three carbon atoms is generally suppressed by competitive photodissociation processes (e.g., Lucas & Liszt 2000). The c-C$_3$H$_2$/CCH ratio is indeed found to be less than 0.1 in both IC10 and the LMC clouds, which is lower than that observed in the Galactic
translucent clouds (0.22; Turner et al. 1999, 2000). The ratio is rather consistent with the ratio in some Galactic diffuse clouds observed in absorption against the bright continuum sources (0.04; Lucas & Liszt 2000) and the ratio in M82, which also hosts extended PDRs (0.04; Fuente et al. 2005; Aladro et al. 2015). This fact further supports the extended PDR in the low-metallicity galaxies.

The non-detection of CH$_3$OH is notable, as in the case of the LMC clouds (Nishimura et al. 2016). We obtained the upper limits of the CH$_3$OH intensity and the column density in IC10. The abundance ratio of CH$_3$OH/HCO$^+$ in IC10 is $< 2.2$, which seems lower than that found in M51 (3.8$^{+3.8}_{-2.3}$). This result can also be interpreted in terms of a stronger UV effect owing to the low abundance of dust grains in IC10. CH$_3$OH is thought to be produced by the hydrogenation of CO on dust grains, and is liberated into the gas phase by thermal and/or non-thermal desorption (e.g., Watanabe & Kouchi 2002). A low abundance of dust grains tends to make the CH$_3$OH formation inefficient. Furthermore, laboratory experiments show that the efficiency of CH$_3$OH formation significantly decreases at temperatures higher than 20 K due to a decreased probability of sticking a hydrogen atom (Watanabe et al. 2003). Since the temperature of cloud peripheries is expected to be higher in the low-metallicity condition due to the penetration of UV radiation, CH$_3$OH would not efficiently form. According to Shimomish et al. (2016), the lower abundance of CH$_3$OH ice observed in the LMC may also be caused by a relatively high dust temperature. Their result is consistent with ours.

We also evaluated the HNC/HCN ratio in IC10 to be 0.22$^{+0.11}_{-0.08}$, which is comparable to the ratio in the LMC clouds, and is lower than the ratio in typical dark clouds (0.54–4.5; Hirota et al. 1998) in the Solar neighborhood. It is close to the ratio reported in some Galactic diffuse clouds, where the HCN and HNC lines are detected in absorption against bright continuum sources (0.21 ± 0.05; Liszt & Lucas 2001). Hirota et al. (1998) reported that the HNC/HCN ratio is lower under higher temperature environments: the ratio decreases above 24 K, possibly reflecting isomerization mechanisms of HNC to HCN. The relatively low ratios observed in IC10 and the LMC clouds may also originate from warmer temperature conditions due to higher UV field and/or lower grain abundances. In addition, it is worth noting the non-detection of N$_2$H$^+$. This seems to originate mainly from the low elemental abundance of nitrogen. In addition, UV radiation may also contribute to the low-abundance of N$_2$H$^+$. The deeper penetration of UV radiation enhances the abundance of atomic ions and electrons, which efficiently destroys N$_2$H$^+$ (Aikawa et al. 2015).

5. SUMMARY

The molecular-cloud-scale chemical composition of IC10 is found to be very similar to that of the LMC clouds. It is characterized by deficiency of N-bearing molecules, relatively high abundant CCH, and a deficiency of CH$_3$OH. Hence, these chemical features can be regarded as being characteristic of low-metallicity galaxies, although they must be further examined in other galaxies with various metallicities. Furthermore, more sensitive observations are needed to detect larger molecules and explore the molecular evolution in low-metallicity galaxies.

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