ALMA Astrochemical Observations of the Infrared-luminous Merger NGC 3256

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Abstract

In external galaxies, molecular composition may be influenced by extreme environments such as starbursts and galaxy mergers. To study such molecular chemistry, we observed the luminous infrared galaxy and merger NGC 3256 using the Atacama Large Millimeter/submillimeter Array. We covered most of the 3 and 1.3 mm bands for a multispecies, multitransition analysis. We first analyzed intensity ratio maps of selected lines such as HCN/HCO⁺, which shows no enhancement at an active galactic nucleus. We then compared the chemical compositions within NGC 3256 at the two nuclei, tidal arms, and positions with influence from galactic outflows. We found the largest variation in SiO and CH₃OH, species that are likely to be enhanced by shocks. Next, we compared the chemical compositions in the nuclei of NGC 3256, NGC 253, and Arp 220; these galactic nuclei have varying star formation efficiencies. Arp 220 shows higher abundances of SiO and HC₃N than NGC 3256 and NGC 253. Abundances of most species do not show a strong correlation with star formation efficiencies, although the CH₃CCH abundance seems to have a weak positive correlation with the star formation efficiency. Lastly, the chemistry of spiral arm positions in NGC 3256 is compared with that of W51, a Galactic molecular cloud complex in a spiral arm. We found higher fractional abundances of shock tracers, and possibly also a higher dense gas fraction in NGC 3256 compared with W51.

Key words: astrochemistry – galaxies: abundances – galaxies: individual (NGC 3256, Arp 220, NGC 253) – galaxies: ISM – galaxies: starburst – ISM: molecules

Supporting material: figure set, machine-readable table

1. Introduction

The molecular composition (or simply “chemistry”) of various species in the interstellar medium (ISM) varies with the environment surrounding the molecular clouds. Although the dominant species in molecular regions is H₂, and the second most abundant molecule, CO, is most commonly observed, more minor species are more sensitive to physical conditions. For example, the compositions of those minor species vary with the stages of star formation or with external radiation, such as UV photons, X-rays, cosmic-rays, or shocks (see Harada 2017 and references therein). Molecular composition also changes as a molecular cloud evolves from diffuse clouds to form denser cores before star formation.

Despite faint emission due to large distances, about 60 species have been previously detected in external galaxies. In starburst galaxies, the chemistry is likely to show features of photon-dominated regions (PDRs) due to the high UV-photon flux. At the same time, starburst galaxies may have higher fractions of dense, star-forming gas compared to galaxies with lower star formation rates. If so, this difference in the ISM properties can also affect the chemistry.

The recent development of Atacama Large Millimeter/submillimeter Array (ALMA) and some pre-ALMA radio interferometers has opened up the possibility of spatially resolved astrochemistry in external galaxies (e.g., Meier & Turner 2005; Takano et al. 2014; Viti et al. 2014; Martín et al. 2015; Meier et al. 2015; Nakajima et al. 2015). The chemical compositions seen in those observations vary with galaxy types. One of the most characteristic chemical compositions is seen in so-called compact obscured nuclei (CONs). CONs are extremely compact (< tens of parsecs), obscured (A_V > 10^10 L☉), and luminous (>10^10 L☉) nuclei in some ultra-luminous infrared galaxies (U/LIRGs). For example, Arp 220 and NGC 4418 have CONs, and have very high abundances of HC₅N or CH₃CN (Martín et al. 2011; Costagliola et al. 2015). In the Galaxy, these molecules are usually seen only toward star-forming regions, and their abundances averaged in the galaxy scale are very low. Even in local starburst galaxies such as NGC 253 and M82, these molecules are much less abundant than in CONs. In addition, CONs have strong emission of vibrationally excited lines (Sakamoto et al. 2010; Aalto et al. 2015b; Martín et al. 2016) with upper state energies ranging from a few hundreds to ~1000 K. Their detections suggest strong infrared radiation for the excitation. Because of the high degree of obscuration, it is still unclear whether these chemical features are caused by extreme starbursts or active galactic nuclei (AGNs), or by the compactness of the nuclei.

What the observed chemistry is most sensitive to in external galaxies is still unknown, partly because of the lack of previous observations, and partly because of the complexity contained in beams that are typically the size of giant molecular clouds or larger. In starburst galaxies, the abundance of molecular species associated with dense cores could correlate with the current star formation rate. However, the correlation may not be tight because the dense cores are ingredients for future star formation, and they may be at various stages of forming massive stars used...
to measure the star formation rate. This time delay is suggested in the molecular study of NGC 253 by Ando et al. (2017), where the chemistry significantly varies among clumps with similar star formation rates. Another driving force of the chemistry is feedback from the existing stars such as irradiation from UV photons (e.g., Martin et al. 2009). To understand the mechanisms behind the chemical composition, it is important to observe starburst galaxies with various star formation rates.

NGC 3256 is an ideal target for such a test. NGC 3256 (D = 35 Mpc, 170 pc/1") is a late-stage merger (by the definition of merger stage by Stierwalt et al. 2013, i.e., two nuclei in a common envelope). An intense starburst caused by the merging activity generates a high infrared luminosity of $L_{IR} = 3 \times 10^{11} L_{\odot}$. Star formation rates in the northern and the southern nuclei (N and S nuclei hereafter) are 15 $M_{\odot}$ yr$^{-1}$ and 6 $M_{\odot}$ yr$^{-1}$ respectively, according to the spectral energy distribution fitting in the near- and mid-infrared wavelengths (Lira et al. 2008). The total star formation rate within this galaxy is estimated to be $\sim 50 M_{\odot}$ yr$^{-1}$ (Sakamoto et al. 2014), and it is expected that the star formation rate even in off-nucleus positions should still be much higher compared with local starburst galaxies such as NGC 253 (total SFR $\sim 5 M_{\odot}$ yr$^{-1}$).

Although the main energy source of NGC 3256 is known to be the starburst event, there are other interesting features that can be studied in NGC 3256. One of them is the AGN in the S nucleus. The configuration of the southern galaxy is almost edge on, and the very central part of the S nucleus is highly obscured. Therefore, the presence of an AGN in the S nucleus lacked convincing evidence (e.g., Lira et al. 2002). Recently, Ohyama et al. (2015) revisited this issue using IR and X-rays, and found that the fit shows an AGN-like feature in the S nucleus. Such AGN/starburst activities are giving feedback to the ISM in NGC 3256. From the velocity components shifted from the range expected from the galaxy rotation, outflows are detected in ionized gas (Leitherer et al. 2013), cold molecular gas (Sakamoto et al. 2006b, 2014), and hot molecular gas (Emonts et al. 2014). Sakamoto et al. (2014) found that the energy in the outflow from the N nucleus can be explained by star formation alone, but the outflow from the S nucleus cannot be accounted for just by a starburst and needs the presence of an AGN. By studying the chemistry of NGC 3256, we can examine various topics such as the effects of star formation, merging events, and outflows on the molecular compositions.

In this paper, we present a molecular line survey to cover most of ALMA Bands 3 and 6 to study the chemical abundances at locations within the central kiloparsec of NGC 3256. The organization of this paper is as follows. In Section 2, we explain our observations and analysis. The results obtained from those observations are described in Section 3 for the continuum and molecular lines. Then, the column densities of individual molecules and their ratios are discussed in Section 4. In Section 5, we further discuss the implication of the results in Sections 3 and 4. Finally, we summarize our findings in Section 6.

### Table 1: Observational Parameters

| ID     | Array | Cycle | config | Observation Date | $N_{int}$ | Baseline Range (m) | $T_{int}$ (minutes) | LSB Range (GHz) | USB Range (GHz) |
|--------|-------|-------|--------|-----------------|-----------|-------------------|-------------------|-----------------|-----------------|
| Band3_a| 12 m  | 3     | C40-3  | 2016 May 28     | 39        | 15–704.1          | 47.3              | 85.49–89.07     | 97.24–100.89    |
| Band3_b| 12 m  | 4     | C40-6  | 2016 Oct 29     | 40        | 18.4–1107.2       | 46.7              | ...             | ...             |
| Band3_c| 12 m  | 3     | C36-2/3 | 2016 Apr 30     | 36        | 15.7–649.4        | 46.2              | 88.91–92.49     | 100.91–104.49   |
| Band3_d| 12 m  | 4     | C40-6  | 2016 Oct 22     | 39        | 18.2–1291.2       | 13.1              | ...             | ...             |

**Archival Data (2015.1.000103.S)**

| ID     | Array | Cycle | config | Observation Date | $N_{int}$ | Baseline Range (m) | $T_{int}$ (minutes) | LSB Range (GHz) | USB Range (GHz) |
|--------|-------|-------|--------|-----------------|-----------|-------------------|-------------------|-----------------|-----------------|
| Band3_a| 12 m  | 3     | C36-1/2 | 2016 Mar 4      | 42        | 13.6–429.4        | 33.3              | 84.26–87.63     | 96.30–99.86     |
| Band3_b| 12 m  | 3     | C36-1/2 | 2016 Mar 7      | 40        | 13.7–429.4        | 33.3              | ...             | ...             |
| Band3_c| 12 m  | 3     | C36-2/3 | 2016 Mar 8      | 44        | 13.1–438.9        | 32.8              | 86.89–90.45     | 98.93–102.49    |
| Band3_d| 12 m  | 3     | C36-2/3 | 2016 Mar 9      | 41        | 13.9–428.2        | 33.8              | 94.56–97.83     | 106.06–109.62   |
| Band3_e| 12 m  | 3     | C36-2/3 | 2016 Mar 11     | 39        | 13.6–426.3        | 33.8              | ...             | ...             |
2. Observations

Our ALMA observations (project code 2015.1.00412.S and 2016.1.00965.S) span through Cycles 3 and 4 using the 12 m array and Atacama Compact Array (ACA) for higher-frequency observations. The observation parameters are summarized in Table 1. For better signal-to-noise ratio (S/N), we also used ALMA data 2015.1.00993.S in the archive for frequency ranges overlapping with ours. To get the data on the CN (1−0) line, we also used ALMA data 2011.0.00525.S, whose observational parameters are described in Sakamoto et al. (2014). Our observations covered most of Bands 3 and 6. For calibration, we ran the pipeline calibration script using CASA version 4.5.3 for cycle 3 data and version 4.7 for cycle 4 data. Then, we checked the amplitude and phase stability of the pipelined data, and no major problem was found. We note that the calibrator of the scheduling block B6_h taken in cycle 4 has fluctuations near the atmospheric absorption at 258 and 271 GHz because the frequency dependence of $T_{\text{sys}}$ there was not accurately corrected due to channel smoothing. Since this fluctuation only affects specific frequencies and there are no lines of interest around these frequencies, we proceed with those calibrated data. To improve the accuracy of flux calibration, we corrected the flux using the continuum fluxes as follows. Continuum flux values at both nuclei were plotted as a function of frequency. Then, we fitted them with the power law $\nu^{\alpha}$ ($\nu$: frequency) for Band 3 and Band 6 separately. We determined the scaling factor for each sideband and each nucleus to match the power-law fit. By taking the average of scaling factors between both sidebands and nuclei, we determined the degree of correction for the amplitude error. We applied this correction to scheduling blocks with more than 3% discrepancy from the power-law fit. Our resulting flux errors should be within $\sim$5%. Imaging and simple image analysis were done with CASA version 4.6. Missing fluxes were evaluated by comparing the images with ACA and without ACA. Since we do not have ACA data for all of the scheduling blocks, we used HCN(3−2), HCO$^+$(3−2), and C$^{18}$O(2−1) for this comparison, and the estimated missing fluxes are 4.7%, 0.2%, and 2.8%, respectively. We do not have ACA data for $^{13}$CO, and the missing flux is expected to be higher for this line because of the extended emission.

3. Observational Results

Before we explain our results later in this section, we briefly explain the morphology of NGC 3256 for clarity. In NGC 3256, the northern and southern nuclei are indicated by “N” and “S” in Figure 1 (left). The spiral arm positions are indicated by “C” (central peak), “TNE” (tidal arm northeast), “TSE” (tidal arm southeast), and “TSW” (tidal arm southwest). The position of the outflow from the S galaxy is indicated by “OS” (outflow south). There is also a peak at western part of the S galaxy (south galaxy west indicated by “SW”). At position OS and around position C, there are components blueshifted/redshifted from the systemic velocity (Figure 1, middle), which are thought of as outflow components. These high-velocity components were already found with CO by Sakamoto et al. (2014) at similar positions. A proposed image for this galaxy merger system, similar to the one in Sakamoto et al. (2014), is shown in Figure 1 (right).

3.1. Continuum Emission

Continuum images at $\lambda = 3.0$ mm and 1.2 mm are shown in Figure 2. The images at these two wavelengths are similar to each other, and to continuum images at 2.81 mm and 0.86 mm in Sakamoto et al. (2014). Those images are overall similar to the radio continuum image at 3.6 cm by Neff et al. (2003), but only the 3.6 cm image has the feature south of the southern galaxy at the position of the outflow from the S nucleus (see Figure 16 of Sakamoto et al. 2014 for the 3.6 cm feature at the position of the outflow). The spectral indices $\alpha$ of the N and S nuclei, where $S_{\nu} \propto \nu^{\alpha}$, are derived using the continuum data using each scheduling block in each sideband. We use only the PI data (2015.1.00412.S and 2016.1.00975.S) for the fit, and the fits were obtained for Band 3 and Band 6 separately. Continuum flux densities within $2''$ are plotted in Figure 3. Each sideband has about a 3.6 GHz width, and the frequency ranges of each sideband can be found in Table 1. Those values are obtained after convolving all the images to $2''$. For the northern nucleus, $\alpha = -0.39 \pm 0.10$ for Band 3, and

$^8$ Although it is likely that those arms are influenced by tidal interaction, we note that not all of the spiral arms may have a tidal origin. It is known from simulations and observations that galaxy mergers can create such arm-like features through tidal interaction (e.g., D’Onghia et al. 2010; Haan et al. 2011).
$\alpha = 1.99 \pm 0.09$ for Band 6. In Band 3, the value in the southern nucleus is equivalent to that in the northern nucleus ($\alpha = -0.37 \pm 0.08$), but in Band 6, it is lower than that in the northern nucleus ($\alpha = 1.16 \pm 0.10$). Values obtained from $f_{\text{obs}} = 85.5-110.3$ GHz are lower than the ones obtained from $f_{\text{obs}} = 99.6-115.0$ GHz by Sakamoto et al. (2014), which are $-0.12$ for the northern nucleus and $-0.19$ for the southern nucleus. This is reasonable because there should be more contribution from synchrotron radiation ($\alpha \sim -1$) than the contribution from free–free emission ($\alpha \sim -0.1$) at the lower frequency. At the same time, this level of change in $\alpha$ can be easily caused by the flux error, which seems to be a more likely cause (see Figure 3). Similarly, values of $\alpha$ at $\lambda = 0.86$ mm in Sakamoto et al. (2014) are higher than the ones at $\lambda = 1.2$ mm because the dust emission ($\alpha \sim 3-4$) has more contribution at the higher frequency.

### 3.2. Molecular Line Images

Velocity-integrated moment maps of selected molecular lines and a radio recombination line (H40$\alpha$) are shown in Figures 4 and 5. In those images, the primary beam is not corrected. The sizes of the primary beams are 51.5/100 (GHz), and most of the emission is within 10". For each transition and without taking line blending into account, we integrated the velocity range $\pm 165$ km s$^{-1}$ around the transition to produce the moment 0 maps. The image parameters and rms values of those images are listed in Table 2. For molecules with doublet or triplet transitions such as CN or CCH, we integrated the velocity ranges of all transitions. The main structures such as the two nuclei, tidal arms, and the outflow (see Figure 1, right panel, for a schematic image) are well-traced by major lines such as $^{13}$CO, C$^{18}$O, HCN, and HCO$^+$, while weaker molecular lines are detected only in selected positions. The spatial distribution of emission intensities of some molecular lines are obviously different from that of CO isotopologues. For example, the distribution of SiO(2–1) is enhanced in the position between the two nuclei and the southwest tidal arm position (Figure 5). The integrated intensity maps of methanol (CH$_3$OH) also have different distributions from those of CO isotopologues, although transitions at 96.7 GHz and around 241 GHz have a different distribution from each other as well (Figure 5). For both transitions of methanol, the emission at the two nuclei is not dominant, and the emission from tidal arms or the outflow is more visible. For the transition at 96.7 GHz, the emission from the northern nucleus is not obvious while it is visible in 241 GHz. Another molecule with a significantly different distribution from CO isotopologues is N$_2$H$^+$. Although other molecules have some contribution from both nuclei, N$_2$H$^+$ is very weak in the S nucleus. Those features mentioned here will be quantitatively analyzed and discussed in Section 4.

#### 3.2.1. Ratio Maps

The spatial variations of intensity ratios are more clearly shown in the ratio maps. In Figure 6, the ratios of molecular emission intensities in Kelvin units are shown. Primary beams are corrected for each moment 0 map before the ratios are taken to produce these images. The HCN(1–0)/$^{13}$CO(1–0) ratio is higher in the N nucleus than in the S nucleus (Figure 6, left). This ratio is also high at the outflow position of the southern galaxy. The HCN(1–0)/HCO$^+$(1–0) ratio is $\sim 1.0$ in the N nucleus while it is $\sim 0.6$ in the S nucleus, and it is lower in the S nucleus than in the N nucleus. This HCN(1–0)/HCO$^+$(1–0) ratio was suggested as an AGN/starburst diagnostic first by Kohno et al. (2001), and later followed by Izumi et al. (2016) and Privon et al. (2017). Results by Kohno et al. (2001; HCN/HCO$^+$ for $J = 1-0$) and Izumi et al. (2016; HCN/HCO$^+$ for $J = 4-3$ and HCN(4–3)/CS(7–6)) show that the values of HCN/HCO$^+$ or HCN/CS are lower in the starburst galaxies (HCN/HCO$^+ < 1$ for both transitions) than in the AGN-containing galaxies (HCN/HCO$^+ \sim 1$–3). At the same time, Izumi et al. (2016) pointed out that the high-resolution data of AGN-containing galaxies do not show enhanced HCN(1–0)/HCO$^+$(1–0) at the location of AGNs (see also García-Burillo et al. 2014; Martín et al. 2015 for the data on the individual galaxies). On the other hand, Privon et al. (2017) found that there is no significant difference between starburst and AGN-containing galaxies for the sample.
of LIRGs, possibly due to the high opacity. Even for LIRGs, Imanishi & Nakanishi (2014) argued that AGNs show elevated HCN(4−3)/HCO+(4−3) ratios in their ALMA observations. In NGC 3256, the S nucleus is the one that shows past AGN activity although it has the lower HCN(1−0)/HCO+(1−0) ratio showing the opposite trend from the AGN/starburst diagnostic mentioned above. The ratios in both nuclei are within the range of values in typical starburst galaxies. Even in AGN-containing galaxies, the line ratios may become similar to those in starburst galaxies if the beam sizes are too large. However, it is unlikely that the observed ratios in NGC 3256 from our observations show starburst-like line ratios of HCN(1−0)/HCO+(1−0) simply because of beam smearing. The beam size of our ratio map is 230 pc, which is equivalent to or smaller than the beam sizes in Kohno et al. (2001) and “high-resolution samples” in Izumi et al. (2016). Although we cannot make a direct comparison with line ratios for different transitions, both HCN(1−0)/HCO+(1−0) and HCN(1−0)/CS (2−1) show similar ratio to values of HCN(4−3)/HCO+(4−3) and HCN(4−3)/CS(7−6) for the samples of starburst galaxies shown in Izumi et al. (2016). The intensity ratios of HNC(1−0)/HCN(1−0) do not differ significantly between the N and S nuclei. The variation of these ratios reflect either the change in molecular abundances or excitation.

Some features can be attributed to the change in the excitation and critical densities. For example, if the mean density in the N nucleus is higher than that in the S nucleus, it can explain the higher HCN(1−0)/13CO(1−0) and HCN(1−0)/HCO+(1−0) ratios in the N nucleus. The critical densities of 13CO, HCO+, and HCN for J = 1−0 transitions are \( n_{\text{crit}} \approx 2 \times 10^3 \text{ cm}^{-3} \), \( 2 \times 10^4 \text{ cm}^{-3} \), and \( 1 \times 10^5 \text{ cm}^{-3} \), respectively.9

On the other hand, the HNC(1−0)/HCN(1−0) ratios cannot be explained solely by the excitation. The critical density of HNC(1−0) is \( n_{\text{crit}} \approx 3 \times 10^5 \text{ cm}^{-3} \), and the HNC(1−0)/HCN(1−0) ratio should be lower in the N nucleus if the critical density is the only contributing factor. It has been pointed out that molecules emit at densities 1–2 orders of magnitudes lower than critical densities (Shirley 2015), and also that the distribution of molecular emission within GMCs do not vary as expected from the critical density alone, due to both excitation and chemical abundances (Kaufmann et al. 2017; Nishimura et al. 2017; Pety et al. 2017; Watanabe et al. 2017). Watanabe et al. (2017) and Nishimura et al. (2017) examined the fractions of molecular line intensities coming from extended diffuse components and denser star-forming regions in Galactic GMCs. Among the species mentioned above, 13CO, HCN, HCO+, and HNC, their results suggest that 13CO emission has more contribution from more extended regions, HCN and HCO+ emission from more compact regions, and HNC has the highest contribution from the compact star-forming regions, probably from dense, yet still cold, gas. If the distribution of molecular emission in the nuclei of NGC 3256 is similar to that of Galactic GMCs, the observed line ratios can be explained if the N nucleus has a greater fraction of dense and compact clouds than the S nucleus. However, we should also note that Meier & Turner (2005) did not see any temperature dependence of the HNC/HCN intensity ratio in the starburst galaxy IC 342, possibly because of high opacity. Another explanation for the lack of temperature dependence is from the high ionization rate, which can create a higher abundance of HCNH+ to form HNC through the recombination with an electron (Aalto et al. 2002).

Another feature to note is the higher HCN(1−0)/13CO(1−0) ratio in the outflow position. It is surprising if it is due to the higher density in the outflow because outflows are usually considered to be hot and tenuous. This feature might be a reflection of the higher fractional abundance10 of HCN due to the higher gas temperature (Loenen et al. 2008; Harada et al. 2010) possibly due to shocks (Aalto et al. 2012; Martín

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9 The critical densities listed here are estimated by simply assuming the two level approximations without considering photon trapping and taking \( n_{\text{crit}} = A_{ul}/\gamma_{ul} \), where \( A_{ul} \) is the Einstein A coefficient for a transition from level u to level l, and \( \gamma_{ul} \) is a collisional coefficient for a transition from level u to level l. The values of \( A_{ul} \) and \( \gamma_{ul} \) were obtained from the Leiden Atomic and Molecular Database (Schöier et al. 2005). A temperature of 10 K was assumed for \( \gamma_{ul} \).

10 Fractional abundances refer to abundances of certain species over total hydrogen or molecular hydrogen abundances. In this paper, we discuss the variation of fractional abundances from abundances of certain species over some reference species such as 13CO or CS because of the difficulty of obtaining the total hydrogen abundances.
A higher HCN(1−0)/CS(2−1) and a lower HNC(1−0)/HCN(1−0) also support this scenario. On the other hand, HCN(1−0)/HCO+(1−0) does not show strong enhancement at the outflow position. It is possible that HCO+ is also enhanced due to ionization in the outflow, but the precise density structure and molecular abundances need to be further explored. However, this enhancement may also be due to the higher density, similar to the case of the outflow in Mrk 231 (Aalto et al. 2015a).

3.3. Molecular Spectra

To analyze individual positions of interest, we extracted spectra from our image cubes. For this analysis, we use the
primary-beam corrected cubes. Since we did not have ACA data for all of the Band 6 scheduling blocks, we only used the 12 m data for consistency. The spectra used to calculate column densities in the next section are produced by convolving the image cubes to a common 1''7 resolution. The rms values of individual spectral windows are listed in Table 3. To include the CN(1−0) line in the analysis, we also used the data produced for Sakamoto et al. (2014). The positions we
Table 2
Image Parameters Used to Create the Moment 0 Maps in Figures 4–5 and Their Cube Properties

| Line          | Weighting | Beam Size (") | rms (mJy beam\(^{-1}\) km s\(^{-1}\)) |
|---------------|-----------|---------------|--------------------------------------|
| \(^{13}\)CO(1–0) | rob1      | 1.50 × 1.44   | 31.7                                 |
| \(^{13}\)CO(2–1) | rob2tp0.5 | 1.06 × 0.98   | 82.9                                 |
| C\(^{18}\)O(1–0) | rob1      | 1.51 × 1.44   | 19.8                                 |
| C\(^{18}\)O(2–1) | rob2tp0.5 | 1.07 × 1.01   | 56.1                                 |
| HCN(1–0) | rob0       | 0.73 × 0.61   | 28.5                                 |
| HCN(3−2) | rob2tp0.5 | 0.94 × 0.91   | 81.6                                 |
| HCO\(^{+}\)(1−0) | rob0     | 0.73 × 0.61   | 30.4                                 |
| HCO\(^{+}\)(3−2) | rob2tp0.5 | 0.94 × 0.90   | 113.6                                |
| HNC(1−0) | rob2      | 1.69 × 1.48   | 21.0                                 |
| HNC(3−2) | rob2tp0.5 | 0.98 × 0.87   | 71.6                                 |
| CS(2−1) | rob1       | 1.65 × 1.60   | 20.7                                 |
| CS(5−4) | rob2tp0.5 | 1.00 × 0.94   | 64.6                                 |
| CH\(_3\)OH(2−1\(_a\)) | rob1 | 1.68 × 1.62 | 17.9                                 |
| CH\(_3\)OH(5−4\(_a\)) | rob2tp0.5 | 0.99 × 0.94 | 67.8                                 |
| CCH(1−0) | rob2      | 1.37 × 1.16   | 31.2                                 |
| CCH(3−2) | rob2tp0.5 | 0.81 × 0.73   | 64.1                                 |
| CN(2−1) | rob2tp0.5 | 1.03 × 1.01   | 129.1                                |
| SiO(2−1) | rob2      | 1.56 × 1.32   | 16.4                                 |
| H\(_4\)O\(_a\)) | rob2 | 1.38 × 1.22   | 12.4                                 |
| N\(_2\)H\(^+\)(1−0) | rob2 | 1.15 × 1.06 | 35.4                                 |
| CH\(_3\)C\(_2\)H\(_6\)(6−5\(_a\)) | rob2 | 1.50 × 1.32 | 19.7                                 |
| CH\(_3\)C\(_2\)H\(_6\)(13−12\(_a\)) | rob2tp0.5 | 1.07 × 1.01 | 63.6                                 |
| HC\(_3\)N(12−11) | rob1 | 1.50 × 1.45 | 18.6                                 |
| HC\(_3\)N(10−9) | rob2 | 1.68 × 1.47 | 19.6                                 |

Note. For the weighting, rob indicates that it was imaged with a robust parameter \(a\), and rob\(_{\text{tp}0.5}\) indicates that it was imaged with a robust parameter \(a\) using uv-taper with the “outertaper” parameter in the CASA task clean set to \(b\) arcsec.

Table 3
Values of rms in Each Scheduling Block after the Beam was Convolved to 1"\(_a\) × 1"\(_b\)

| ID          | \(f_{\text{rest}}\) (GHz) | Band | rms (mJy beam\(^{-1}\)) |
|-------------|--------------------------|------|------------------------|
| Band3\(_a1\) | 85.49–87.63              | LSB  | 0.181                  |
| Band3\(_a1\) | 97.24–99.86              | USB  | 0.215                  |
| Band3\(_a2\) | 87.63–89.07              | LSB  | 0.193                  |
| Band3\(_a2\) | 99.86–100.89             | USB  | 0.217                  |
| Band3\(_b1\) | 88.91–90.45              | LSB  | 0.181                  |
| Band3\(_b1\) | 100.91–102.49            | USB  | 0.200                  |
| Band3\(_b2\) | 90.45–92.49              | LSB  | 0.484                  |
| Band3\(_b2\) | 102.49–104.49            | USB  | 0.533                  |
| Band3\(_c\)  | 94.71–97.83              | LSB  | 0.165                  |
| Band3\(_c\)  | 106.71–109.62            | USB  | 0.192                  |
| Band6\(_a\)  | 214.06–217.71            | LSB  | 0.633                  |
| Band6\(_a\)  | 230.06–233.71            | USB  | 0.692                  |
| Band6\(_b\)  | 217.61–221.26            | LSB  | 0.898                  |
| Band6\(_b\)  | 233.61–237.26            | USB  | 0.932                  |
| Band6\(_c\)  | 221.16–224.81            | LSB  | 0.793                  |
| Band6\(_c\)  | 237.16–240.81            | USB  | 0.860                  |
| Band6\(_d\)  | 224.71–228.36            | LSB  | 0.867                  |
| Band6\(_d\)  | 240.71–244.36            | USB  | 0.993                  |
| Band6\(_e\)  | 244.79–248.43            | LSB  | 0.847                  |
| Band6\(_e\)  | 258.98–262.62            | USB  | 0.931                  |
| Band6\(_f\)  | 248.32–251.96            | LSB  | 1.002                  |
| Band6\(_f\)  | 262.51–266.15            | USB  | 1.202                  |
| Band6\(_g\)  | 251.87–255.51            | LSB  | 0.869                  |
| Band6\(_g\)  | 266.06–269.70            | USB  | 1.043                  |
| Band6\(_h\)  | 255.44–259.08            | LSB  | 0.888                  |
| Band6\(_h\)  | 269.63–273.27            | USB  | 1.047                  |
analyzed are shown in Figure 1 (left) as discussed at the beginning of Section 3 (N: northern nucleus, S: southern nucleus, C: central peak, TNE: tidal arm northeast, TSE: tidal arm southeast, TSW: tidal arm southwest, OS: outflow south, SW: southern galaxy west). Note that in the analysis of column densities in the later sections, we use the entire velocity range around the systemic velocity for the position OS, and some contamination from non-outflow components is possible. Plots of spectra are shown in Figure 7 (Set 1). The observed peak intensities and integrated intensities are listed in Table 4 for detected species and tentatively detected species with $>2\sigma$ at the peak. The integrated intensities are calculated by integrating a velocity range of $\pm 150$ km s$^{-1}$ from the systemic velocity of 2775 km s$^{-1}$. Errors for the integrated intensities are estimated as $\Delta I / \Delta v \sqrt{N}$, where $\Delta I$ is the rms of the original cube corrected according to the position in the primary beam, $\Delta v$ is the velocity resolution of the cube, and $N = v_{\text{range}} / \Delta v$ for $v_{\text{range}} = 300$ km s$^{-1}$. If lines are narrower than $v_{\text{range}} = 300$ km s$^{-1}$, the actual errors may be smaller. That is why some of the weak lines have low values of $I \Delta v$.

Although the molecular line spectra can be fit with a single Gaussian profile in most positions, there are exceptions. For example, spectrum shapes of the N and S nuclei have double peaks for most of the species. It is likely that these double peaks come from the rotation of the galactic nuclei and not from self-absorption because even molecules that are thought to be optically thin have double peaks. Another position where spectra cannot be fit well with a single Gaussian is the position OS, which can be explained by the complicated velocity structure of the outflow. Line wings from the outflow are detected clearly at the peak position of the redshifted component seen in Figure 1 (middle) for HCN(1−0), HCO$^+$(1−0), and HNC(1−0), shown in Figure 8.

Figure 6. Maps of intensity ratios of (upper left) HCN(1−0)/$^{13}$CO (1−0), (upper right) HCN (1−0)/HCO$^+$ (1−0), (lower left) HNC (1−0)/HCN (1−0), and (lower right) HCN (1−0)/CS(2−1). The ratios are calculated for the intensity units in Kelvin scale. Positions shown in Figure 1 are marked with red crosses.
4. Column Densities

To quantify the spatial variation of the chemical composition, we present the column densities of the detected species in this section using the spectra presented in Section 3.3. To obtain column densities, we used a spectral fitting feature of MADCUBA (S. Martín et al. 2018, in preparation). In this program, the fit between the simulated spectra and the observed one is calculated, and column densities and excitation temperatures with the best fit can be obtained under the LTE approximation. In the simulated spectra, optical depth is also taken into account. The obtained column densities and excitation temperatures are listed in Tables 5–12. The errors shown in those tables are the errors from the fitting. The estimated $T_{\text{ex}}$ are mostly $\lesssim 10$ K, except for HC$_3$N, CH$_3$CCH, CH$_3$OH, and H$_2$CO. For those molecules, $T_{\text{ex}}$ can be as high as 20–40 K. For a molecule with only one line with enough S/N, we used $T_{\text{ex}} = 10$ K. Even with the detection of multiple transitions, there are cases where $T_{\text{ex}}$ cannot be precisely determined. For those cases, $T_{\text{ex}}$ was fixed at the best-fit value.

Figure 7. Observed spectra from 1" resolution cubes at position N in Band 3. Fitted spectra for individual transitions are shown in blue for component 1 and in green for component 2, while the summed intensities of individual transitions are shown in red. Gray dotted lines show the 3σ levels.

(The complete figure set (32 images) is available.)

11 http://cab.inta-csic.es/madcuba/Portada.html
### Table 4

**Observed Peak Intensities and Velocity-integrated Intensities for Detected Lines**

| Position | Species | Transitions | Restfreq (GHz) | $I_{\text{peak}}$ (mK) | $\Delta I_{\text{peak}}$ (mK) | $I \Delta V$ (K km s$^{-1}$) | $\Delta(I \Delta V)$ (K km s$^{-1}$) |
|----------|---------|-------------|----------------|-------------------------|-----------------------------|-------------------------------|-------------------------------|
| N        | $^{13}$CO$^+$ | 1 $-$ 0    | 86.754         | 56.3                    | 10.41                       | 9.4                           | 0.95                          |
| N        | SiO     | 2 $-$ 1    | 86.847         | 40.85                   | 10.39                       | 6.41                          | 0.95                          |
| N        | CCH     | 1$\nu_2$ $-$ 0$\nu_2$ | 87.317         | 373.18                  | 10.28                       | 76.97                         | 0.94                          |
| N        | CCH     | 1$\nu_2$ $-$ 0$\nu_2$ | 87.402         | 201.53                  | 10.26                       | 41.4                          | 0.94                          |
| N        | HCN     | 1 $-$ 0    | 88.634         | 1111.22                 | 10.64                       | 197.23                        | 0.96                          |
| N        | HCO$^+$ | 1 $-$ 0    | 89.189         | 1173.21                 | 10.51                       | 205.25                        | 0.95                          |
| N        | HOC$^+$ | 1 $-$ 0    | 89.487         | 26.83                   | 10.44                       | 3.88                          | 0.94                          |

(This table is available in its entirety in machine-readable form.)

### Table 5

**Column Densities at N**

| Molecule | $N$ (cm$^{-2}$) | $T_{\text{ex}}$ (K) |
|----------|----------------|----------------------|
| $^{13}$CO | $(3.0 \pm 0.1) \times 10^{6.0}$ | 10.5 $\pm$ 0.6 |
| $^{13}$CO | $(2.3 \pm 0.1) \times 10^{6.0}$ | 11.5 $\pm$ 0.7 |
| HCO$^+$ | $(2.8 \pm 0.1) \times 10^{5.0}$ | 10.6 $\pm$ 0.3 |

### Table 6

**Column Densities at S**

| Molecule | $N$ (cm$^{-2}$) | $T_{\text{ex}}$ (K) |
|----------|----------------|----------------------|
| $^{13}$CO | $(2.5 \pm 0.2) \times 10^{10.0}$ | 10.8 $\pm$ 1.1 |
| $^{13}$CO | $(3.4 \pm 0.3) \times 10^{10.0}$ | 8.5 $\pm$ 0.6 |
| HCO$^+$ | $(3.8 \pm 0.7) \times 10^{10.0}$ | 10.6 $\pm$ 2.8 |
| HCO$^+$ | $(6.1 \pm 1.3) \times 10^{10.0}$ | 6.7 $\pm$ 0.9 |
| HCO$^+$ | $(8.1 \pm 1.2) \times 10^{14.0}$ | 10.8 $\pm$ 2.8 |
| HCO$^+$ | $(10.0 \pm 0.2) \times 10^{10.0}$ | 8.5 $\pm$ 0.6 |
| HCO$^+$ | $(8.8 \pm 0.4) \times 10^{13.0}$ | 5.6 $\pm$ 0.1 |
| HCO$^+$ | $(4.9 \pm 0.4) \times 10^{13.0}$ | 5.8 $\pm$ 0.1 |
| HCO$^+$ | $(8.5 \pm 0.3) \times 10^{13.0}$ | 6.7 $\pm$ 0.1 |
| HCO$^+$ | $(4.3 \pm 0.3) \times 10^{13.0}$ | 7.3 $\pm$ 0.2 |
| HCO$^+$ | $(8.5 \pm 0.3) \times 10^{13.0}$ | 6.7 $\pm$ 0.1 |
| HHN$^+$ | $(9.5 \pm 0.4) \times 10^{14.0}$ | 6.9 $\pm$ 0.1 |
| CH$_3$OH | $(7.6 \pm 0.5) \times 10^{10.0}$ | 15.0 $\pm$ 2.0 |
| CH$_3$OH | $(5.1 \pm 0.5) \times 10^{10.0}$ | 15.0 $\pm$ 2.0 |
| H$_2$CO | $(1.2 \pm 0.1) \times 10^{10.0}$ | 18.5 $\pm$ 4.3 |
| H$_2$CO | $(1.4 \pm 0.2) \times 10^{10.0}$ | 35.1 $\pm$ 13.2 |
| CH$_3$CO | $(1.3 \pm 0.1) \times 10^{10.0}$ | 10.0 $\pm$ 2.0 |
| CH$_3$CO | $(8.4 \pm 0.5) \times 10^{12.0}$ | 10.0 $\pm$ 2.0 |
| CH$_3$CH | $(3.2 \pm 0.5) \times 10^{10.0}$ | 13.4 $\pm$ 1.5 |
| CH$_3$CH | $(2.5 \pm 0.3) \times 10^{10.0}$ | 22.3 $\pm$ 3.8 |
| CH$_3$CN | $(2.8 \pm 0.1) \times 10^{10.0}$ | 43.0 $\pm$ 1.7 |
| CH$_3$CN | $(2.3 \pm 0.1) \times 10^{10.0}$ | 45.0 $\pm$ 2.4 |
| CH$_3$CN | $(1.0 \pm 0.0) \times 10^{10.0}$ | 10.0 $\pm$ 2.0 |
| CH$_3$CN | $(6.6 \pm 0.3) \times 10^{12.0}$ | 10.0 $\pm$ 2.0 |
| SO       | $(7.6 \pm 0.9) \times 10^{12.0}$ | 10.0 $\pm$ 2.0 |
| SO       | $(4.7 \pm 0.8) \times 10^{12.0}$ | 10.0 $\pm$ 2.0 |
| H$_3$CO$^+$ | $(4.6 \pm 1.8) \times 10^{12.0}$ | 6.0 $\pm$ 0.7 |
| H$_3$CO$^+$ | $(4.3 \pm 1.8) \times 10^{12.0}$ | 5.1 $\pm$ 0.5 |
| HOC$^+$ | $(1.8 \pm 1.1) \times 10^{12.0}$ | 8.3 $\pm$ 2.1 |
| HOC$^+$ | $(1.6 \pm 1.0) \times 10^{12.0}$ | 8.5 $\pm$ 2.4 |
| c-C$_3$H$_2$ | $(8.5 \pm 1.6) \times 10^{12.0}$ | 17.1 $\pm$ 3.1 |
| c-C$_3$H$_2$ | $(1.2 \pm 0.2) \times 10^{13.0}$ | 15.3 $\pm$ 1.6 |
| SO       | $(2.7 \pm 1.7) \times 10^{13.0}$ | 10.5 $\pm$ 3.7 |
| SO       | $(2.5 \pm 1.4) \times 10^{13.0}$ | 10.4 $\pm$ 3.3 |
| C$_3$S    | $(1.7 \pm 0.7) \times 10^{13.0}$ | 9.4 $\pm$ 1.4 |
| C$_3$S    | $(1.0 \pm 0.5) \times 10^{13.0}$ | 9.8 $\pm$ 2.1 |
| NO       | $(1.0 \pm 0.1) \times 10^{15.0}$ | 10.0 $\pm$ 2.0 |
| NO       | $(8.8 \pm 0.6) \times 10^{14.0}$ | 10.0 $\pm$ 2.0 |
| CO$^+$   | $(1.1 \pm 0.3) \times 10^{13.0}$ | 10.0 $\pm$ 2.0 |
| CO$^+$   | $(1.3 \pm 0.2) \times 10^{13.0}$ | 10.0 $\pm$ 2.0 |
| HNCO     | $(2.5 \pm 0.1) \times 10^{13.0}$ | 30.0 $\pm$ 2.0 |
| HNCO     | $(2.6 \pm 0.1) \times 10^{13.0}$ | 30.0 $\pm$ 2.0 |
| HNCO     | $(2.5 \pm 0.1) \times 10^{13.0}$ | 30.0 $\pm$ 2.0 |
| HNCO     | $(2.6 \pm 0.1) \times 10^{13.0}$ | 30.0 $\pm$ 2.0 |
to obtain column densities. If the molecular species are undetected at certain positions, the upper limits are obtained by deriving column densities for cases of 2σ detections at the lowest (or strongest) transition with $T_{\text{ex}} = 10$ K.

In the following sections, we plot the ratios of the derived column densities. We use two different species with different critical densities ($^{13}$CO and CS) as the denominator of the ratios for the following reasons. Since we have detections of multiple transitions for most of the major species, the derived column densities should result from differences in fractional abundances. However, this is not always the case if the density distribution within the beam is different. If the beam contains a
higher fraction of relatively dense material, then molecules with higher critical densities have a larger area/volume where they can emit. This higher fraction of dense gas can result in higher apparent abundances even when the abundances are derived using multiple transitions. If this excitation factor plays a role in the ratio of column densities, discussions of the variation of fractional abundances are only valid when the column density ratios are obtained using molecules with similar critical densities for both numerator and denominator. $^{13}$CO is a good denominator for molecules with low critical densities while CS is suitable for high $n_{\text{crit}}$ molecules. We have already mentioned in Section 3.2.1 that molecules may emit at lower densities than the critical densities, but molecules such as CS still emit more effectively at higher densities than $^{13}$CO (Nishimura et al. 2017; Watanabe et al. 2017).

4.1. Comparison within NGC 3256

We first compare the chemistry among the eight positions we analyzed in NGC 3256. Here we focus our discussion on selected species such as species with higher critical densities (HCN, HCO$^+$, CS, and CN), species enhanced with shocks (SiO, CH$_3$OH, HNCO), species enhanced in PDRs (CCH, HOC$^+$), and species seen in cold dense cores (N$_2$H$^+$). We also discuss CH$_3$CCH because it was proposed to be an AGN/starburst diagnostic by Aladro et al. (2015). We omit discussion of species detected in three or fewer positions (c-C$_3$H$_2$, CH$_3$CN, and CO$^+$), some isotopologues (H$_2$CO$^+$ and C$_3$4S), and species with little variation among positions (SO, NO, and H$_2$CO). We arrange the column density ratios by CS column densities in descending order in Figures 9–10.

In Figure 9 (top), the column density ratios of molecules with relatively high critical densities over $^{13}$CO are plotted in log scale. To highlight the variation among the locations, the column density ratios over $^{13}$CO normalized to the value at the location “N” are shown in Figure 9 (bottom), also in log scale. The variation of column density ratios seems similar among molecules. Although it is possible that the fractional abundances of those molecules vary among those positions in a similar way, it is likely that the variation of the excitation condition within the beam discussed earlier in Section 4 is changing those apparent fractional abundances.

On the other hand, there is a variation of the derived column density ratios that is likely caused by differences in fractional abundances of certain molecules. The behavior of such
molecules is described below, and column densities are plotted in Figure 10.

SiO: The column density ratios of SiO over \(^{13}\)CO and over CS show an enhancement for both at the position OS. Silicon monoxide is expected to be enhanced in strong shocks of velocity \(v_{\text{shock}} > 25\) km s\(^{-1}\) (Gusdorf et al. 2008) due to sputtering from the dust core. Although it was claimed that there is a correlation between SiO intensity and X-ray strength (Amo-Baladrón et al. 2009), this correlation is a weak one. It is indeed theoretically possible that X-ray heats up the dust enough to make it sublime; SiO as an XDR tracer should be taken with caution. If this outflow is an AGN-induced outflow, both shocks and X-rays are naturally expected.

\(\text{CH}_3\text{OH}\): The column density ratios of \(\text{CH}_3\text{OH}\) vary in a similar way to those of SiO although the enhancement at one of the tidal arm positions (TSW) is also prominent for \(\text{CH}_3\text{OH}\). \(\text{CH}_3\text{OH}\) is known to be enhanced in weak shocks. For methanol, there are other mechanisms to increase its abundance in the gas phase, such as cosmic-ray or UV-induced photodesorption, or chemical desorption. However, chemical desorption should affect the larger galactic scale, and cannot explain the variation within NGC 3256. For the case of cosmic-ray or UV-induced photodesorption, if it is increasing the abundances of methanol, it should be abundant in the two nuclei. The methanol abundances in the two nuclei are rather low. Therefore, if UV photons or cosmic rays affect the methanol abundances, it is likely to make it sublimate; SiO as an XDR tracer should be taken with caution. If this outflow is an AGN-induced outflow, both shocks and X-rays are naturally expected.

Figure 9. (Top) Column density ratios of HCN, HCO\(^+\), CS, and CN over \(^{13}\)CO at positions N, S, C, TNE, TSE, TSW, OS, and SW in NGC 3256. The errors of the individual column densities are automatically calculated from the Gaussian fitting by MADCUBA. (Bottom) The same as the top figure, but with all of the values normalized to position ‘N.” All values are shown in log scale.
other except for the N nucleus. A possible reason for the difference in the N nucleus might be that HNCO and CH$_3$OH abundances may act differently with dust temperature. Methanol abundances decrease at high dust temperature because the hydrogen atom evaporates faster at high dust temperatures, and the hydrogen atom is less likely to react (Acharyya & Herbst 2016). HNCO may be able to sustain its abundance at higher dust temperatures than CH$_3$OH because a smaller number of hydrogen is necessary for HNCO. This temperature dependence of HNCO needs to be tested with chemical models. For the case of SiO column density ratios, there is a good correlation between HNCO column density ratios. Such a correlation between HNCO and SiO was also proposed in Galactic high-mass star-forming regions (Zinchenko et al. 2000). A survey of several galaxies by Martín et al. (2009) also suggested that a higher ratio of HNCO is a characteristic of an early stage of a starburst, which is dominated by shocks, instead of UV photons.

N$_2$H$^+$: In Galactic star-forming regions, N$_2$H$^+$ emission is usually associated with dense cores (e.g., Storm et al. 2014; Pety et al. 2017). In our observations, the column density ratios of N$_2$H$^+$ over CS do not show clear variation, but the ratios over $^{13}$CO show a slightly higher value in the N nucleus than in the S nucleus. It can be explained if the N nucleus contains more dense clouds than the S nucleus, as argued in Section 3.2.

HC$_3$N: In Galactic molecular clouds, higher abundances of cyanoacetylene (HC$_3$N) are usually detected in dense cold clouds or hot protostellar cores. For extragalactic sources, it has been found that CONs such as NGC 4418 and Arp 220 have a high fractional abundance of HC$_3$N (Aalto et al. 2007; Costagliola & Aalto 2010; Lindberg et al. 2011; Martín et al. 2011). Since HC$_3$N is enhanced in star-forming regions, one can expect that HC$_3$N is more enhanced in regions of higher star formation efficiency. Although the N and S nuclei have higher star formation surface densities than other positions (Lira et al. 2008), N(HC$_3$N)/N($^{13}$CO) is the highest in position C, a tidal arm with a possible interaction with the outflow component. It is likely that HC$_3$N fractional abundances are dependent not only on the star formation efficiency, but also on other factors, such as the effects of shocks.

CH$_3$CCH: Propyne (CH$_3$CCH) has been proposed as a diagnostic of starburst versus AGN by Aladro et al. (2015): starburst galaxies have high abundances of CH$_3$CCH while AGN-containing galaxies do not have detections of CH$_3$CCH.
However, the reason behind this observational trend is still unknown. In NGC 3256, although the S nucleus is the likely AGN host, CH$_3$CCH column density ratios in the S nucleus are equivalent to or higher than those in the N nucleus.

HOC$^+$: HOC$^+$ is a metastable isomer of HCO$^+$, and it needs to be irradiated by a strong UV field (Goicoechea et al. 2017) or X-rays (Usoro et al. 2004) to keep its abundance high. In NGC 3256, the positions where HOC$^+$ is enhanced are C and OS, although the detection in OS is also tentative, and the error bars are large. Position OS contains the high-velocity gas coming from the outflow, and position C also contains gas from the redshifted outflow component (Figure 1). A connection between HOC$^+$ abundance and the outflow is suspected. However, the connection between the HOC$^+$ enhancement and the outflow cannot be directly confirmed in the high-velocity gas alone because the high-velocity components are too weak to be detected for HOC$^+$.

CCH: The ethynyl radical (CCH) is known to be enhanced in PDRs (e.g., Cuadrado et al. 2015), but they are also abundant in the early-time chemistry, and has been observed in quiescent starless cores, such as TMC-1(CP) (Smith et al. 2004). Although CCH was also recently found in the outflow from an AGN in NGC 1068 (García-Burillo et al. 2017), its enhancement in the outflow is not seen in NGC 3256. This case is similar to NGC 1097, where no particular enhancement was seen around the AGN for CCH (Martín et al. 2015). Their abundances in NGC 3256 are highest in the N nucleus if the column density ratios are over $^{13}$CO, but there is less variation among positions within NGC 3256 for ratios over CS.

4.2. Comparison with Other Galactic Nuclei

We next compare the chemistry in the nuclear positions in NGC 3256 and that in NGC 253 and Arp 220, galaxies with different star formation rates and efficiencies. The properties of these galaxies are summarized in Table 13.

NGC 253 is a well-studied, nearby starburst galaxy. The molecular gas distribution of the central molecular zone (CMZ) is similar to that of the Milky Way. However, the star formation rate inside is much higher than in the Milky Way CMZ. Yet, NGC 3256 has an even higher star formation rate within its CMZs. For NGC 253, we use the results by Aladro et al. (2015), obtained from the IRAM 30 m telescope. The angular resolution of this IRAM study is 17″–24″, which converts into 300–400 pc. This spatial scale is equivalent to the spatial resolution in our analysis of NGC 3256, which is ∼300 pc.

Like NGC 3256, Arp 220 is also a merger, but has an even higher luminosity than NGC 3256. The nuclear separation of the two nuclei in Arp 220 is ∼400 pc on the sky, which is smaller than in NGC 3256. The column densities in Arp 220 are taken from the results of S. Martín et al. (2018, in preparation), where they used ALMA for the spectral scan of Bands 6 and 7 (see Martín et al. 2016 for some description of these data). The exact values of the column densities and errors will be given in S. Martín et al. (2018, in preparation). Their spatial resolution is also around 300 pc.

We note that the analysis in S. Martín et al. (2018, in preparation) did not use the Gaussian fit to the observed spectra for the calculation of column densities because they are severely affected by absorption at the line center. They use the side of the lines to calculate column densities. Therefore, we claim that the error of the column densities from absorption is minimized, but it cannot be claimed that those values are free from absorption effects.

The column density ratios of the nuclei in NGC 253, NGC 3256, and Arp 220 are plotted in Figures 11 and 12, and these ratios are discussed below.

HCN, HCO$^+$, CS, and CN: The column density ratios of HCN, HCO$^+$, CS, and CN seem to follow similar trends; the ratios are similar in NGC 253 (S and SW) and NGC 253, but the values in NGC 3256 (N and Arp 220 (E and W) are a factor of a few higher. Some exceptions are CN and HCO$^+$ suppressed by a factor of a few in Arp 220 compared with other species, and a slightly enhanced CS in Arp 220 (W).

SiO: Among the galactic nuclei, Arp 220 has the highest column density ratios of SiO both over $^{13}$CO and CS. The spectral shapes observed in Arp 220 strongly suggest that it has molecular outflows from both nuclei (Sakamoto et al. 2009) with the one from the western nucleus being more prominent (Sakamoto et al. 2017). It has been already discussed in Section 4.1 that the outflow from the N nucleus in NGC 3256 does not contribute to the high SiO abundances. Unlike the outflow from the S nucleus in NGC 3256, each outflow in Arp 220 should be within the beam that covers each nucleus. These outflows might be the reason for the higher SiO abundances in Arp 220. An alternative explanation is that there are more cloud–cloud collisions in the dense and compact nuclei of Arp 220.

CH$_3$OH and HNCO: The column density ratios of CH$_3$OH and HNCO are lower in the NGC 3256 nuclei than in NGC 253 and Arp 220. As mentioned above, there are nuclear outflows in Arp 220, which can enhance the methanol and HNCO abundances. At the same time, NGC 253 also has evidence of an outflow from the starburst (Sakamoto et al. 2006a; Bolatto et al. 2013). Alternatively, an enhancement in NGC 253 may be due to the cloud–cloud collision at the intersection of galactic orbits. Similar to SiO, the N nucleus of NGC 3256 does not seem to enhance CH$_3$OH and HNCO by a large amount.

$\text{N}_2\text{H}^+$: Although the column density ratios of $N($N$_2\text{H}^+)/N(^{13}\text{CO})$ vary among the galactic nuclei, the $N($N$_2\text{H}^+)/N(^{13}\text{CO})$ ratios have very little variation. This lack of variation may indicate that the column density ratios of $N($N$_2\text{H}^+)/N(^{13}\text{CO})$ may be a direct measure of dense cloud fraction, and that,
within the dense gas, $N_2H^+$ abundance does not vary much with respect to other molecules tracing the dense gas.

$HC_3N$: Here we can examine the relation between $HC_3N$ fractional abundances and the star formation efficiency ($=\tau_{\text{dep}}^{-1}$, see Table 13). Although galactic nuclei with higher star formation efficiencies tend to have higher $HC_3N/^{13}CO$ ratios, the variation among sources is not as large as the star formation efficiency itself (see also the discussion in Section 5.3).

$CH_3CCH$: Column density ratios $CH_3CCH/^{13}CO$ appear to be higher in sources with higher star formation efficiencies (see Section 5.3). However, as mentioned earlier, the behavior of this molecule is not well-known, and it is unclear what mechanism is causing the enhancement with higher star formation activity.

$HOC^+$: $N(HOC^+)/N(^{13}CO)$ ratios are the highest in Arp 220W, but there is little variation among the galactic nuclei for $N(HOC^+)/N(CS)$. However, if $N(HOC^+)/N(HCO^+)$ is plotted, it is also the highest in Arp 220W (Figure 13). Since $HOC^+$...
$N(\text{HOC}^+)/N(\text{HCO}^+)$ is more reliable because it is not affected by the difference in elemental abundance, HOC$^+$ abundance in Arp 220W is likely higher than in other sources. Since Arp 220W has a prominent outflow, the connection of HOC$^+$ with outflows may be seen here again, but it needs to be confirmed with high-resolution imaging of Arp 220 in HOC$^+$. The effect of starburst in Arp 220 may also be the reason for increased $N(\text{HOC}^+)/N(\text{HCO}^+)$. CCH: Since CCH is known to be a PDR tracer, one might expect higher fractional abundances of CCH in galaxies with higher star formation rates. However, this is not necessarily the case. A possible reason is the differences in the mean density. When the mean density in the ISM is very high, only a fraction of volume can be influenced by UV photons because those photons become attenuated before getting far from the vicinity of OB stars, and the enhancement of PDR tracers cannot be seen on a large scale.

4.3. Comparison with a Galactic Spiral Arm Region

Here we compare the chemical compositions of the tidal arm positions in our study with the one in W51 for a relevant comparison among spiral arm positions. W51 is a molecular cloud complex in the Sagittarius arm in the Milky Way at the distance of 5.4 kpc (Sato et al. 2010). Within W51, there is an active star-forming region, which includes the hot core W51 e1/e2. Watanabe et al. (2017) mapped various molecular species in a $\sim 40$ pc $\times 50$ pc region in W51, and studied the average chemistry within this region so that their results can be compared with extragalactic interferometric observations taken with beam sizes of at least tens of parsecs. We do not discuss HOC$^+$ here because this species was not detected in the averaged spectra of W51. Although their spatial scale is a factor of several smaller than our resolution, we assume that there are molecular clouds with sizes similar to that of W51 within our beam, and we compare the chemistry in the NGC 3256 arm positions and in W51. Since Watanabe et al. (2017) only had data in the 3 mm band, they derived column densities using excitation temperatures of $T_{\text{ex}} = 10, 15$, and 20 K. Because the excitation temperatures of our results are $T_{\text{ex}} = 10$ K or less, we use their column densities using $T_{\text{ex}} = 10$ K. Although the $T_{\text{ex}}$ of some molecules are $\sim 5$ K or so, we checked that the derived column densities do not vary significantly if we derive them by assuming $T_{\text{ex}} = 10$ K for those molecules.

HCN, HCO$^+$, CS, and CN: Molecules with higher critical densities have higher column density ratios over $^{13}$CO at the tidal arm positions in NGC 3256 than in W51 (Figure 14). This trend may indicate a higher fraction of dense clouds in the beam in NGC 3256 tidal arms as discussed at the beginning of Section 4, where we suggest that the variation of these ratios comes from the variation of the dense gas fraction within NGC 3256.

The column density ratios of other species are plotted in Figure 15.

SiO: The column density ratios of SiO both over $^{13}$CO and CS at the position TSW are much higher than the upper limit in W51. This high abundance of SiO indicates more strong shocks in position TSW of NGC 3256, possibly caused by the merger interaction. The upper limits at positions TNE and TSE are higher than those of W51, hence it is unknown whether these positions have more influence from shocks.

CH$_3$OH and HNCO: Similarly to SiO, the higher column density ratios of methanol and HNCO in NGC 3256 than in W51 are seen for ratios both over $^{13}$CO and CS. Unlike SiO and HNCO, the enhancement is also seen in position TSE as well as in TSW for methanol.

$N_2H^+$: The trend of column density ratios of $N_2H^+$ over $^{13}$CO and CS is similar to that of HC$_3$N. The ratios over $^{13}$CO are higher in the NGC 3256 positions than that in W51, but there is no obvious variation among positions for ratios over CS. Since $N_2H^+$ is also abundant in more compact regions just like HC$_3$N, the same explanation for HC$_3$N can possibly be used for this trend.

HC$_3$N: Ratios $N(\text{HC}_3\text{N})/N(^{13}\text{CO})$ are higher in the tidal arm positions in NGC 3256 than in W51. However, the values of $N(\text{HC}_3\text{N})/N(\text{CS})$ have very little variation among the sources. In Galactic GMCs, HC$_3$N comes from regions more compact than CS. If this is also the case in NGC 3256, our results indicate that within a CS-emitting cloud, there is a similar fraction of HC$_3$N-emitting cores both in NGC 3256 and in W51.

CH$_4$CCH: In the tidal arm positions in NGC 3256, $N(\text{CH}_4\text{CCH})/N(^{13}\text{CO})$ and $N(\text{CH}_4\text{CCH})/N(\text{CS})$ are higher than in W51. The ratio is the highest in TNE, the only off-nucleus position where H40$\alpha$ is detected. A hint of a positive correlation between the star formation rate and CH$_4$CCH is again seen here, but the reason behind it needs more investigation.

CCH: Ratios $N(\text{CCH})/N(^{13}\text{CO})$ have higher values at the tidal arm position of NGC 3256 than in W51, and $N(\text{CCH})/N(\text{CS})$ does not vary much among those positions. This trend is similar to $N_2H^+$ and HC$_3$N. However, CCH having this similarity with $N_2H^+$ and HC$_3$N is puzzling because CCH is usually thought to come from rather extended regions.

5. Discussion

5.1. $^{13}$CO and $^{18}$O Anomaly in LIRGs

It has been pointed out that the $^{12}$CO/$^{13}$CO and $^{12}$C$^{18}$O/$^{18}$O intensity ratios in LIRGs are higher than those in normal spiral galaxies (Aalto et al. 1991; Casoli et al. 1992). Casoli et al. (1992) concluded that $^{13}$CO and C$^{18}$O lines are about four times weaker in NGC 3256 than what is normally expected from $^{12}$CO in their single-dish observations. This variation in intensity ratios can be caused by excitation effects.
such as high temperature or turbulence (Aalto et al. 1991, 2010; Davis 2014). Turbulence can increase \(^{12}\text{CO}/^{13}\text{CO}\) by causing \(^{12}\text{CO}\) to be less optically thick, or turbulence occurs at the position where the low-metallicity gas flows (Henkel et al. 2014; König et al. 2016). If this is the case, our chemistry analysis using the column density ratios \(N(X)/N(^{13}\text{CO})\) is not affected. However, it can also be caused by an abundance deficit of \(^{13}\text{C}\) due to very young starburst or the top-heavy initial mass function as proposed by Sliwa et al. (2017). The abundance ratio of \(^{12}\text{CO}/^{13}\text{CO}\) can also increase by selective photodesorption of \(^{13}\text{CO}\) because \(^{13}\text{CO}\) is less likely to be self-shielded. If it is caused by the elemental abundances of \(^{12}\text{C}/^{13}\text{C}\), our derived column density ratios \(N(X)/N(^{13}\text{CO})\) may reflect the variation of not only \(N(X)\), but also of \(N(^{13}\text{CO})\). If the \(^{12}\text{CO}/^{13}\text{CO}\) column density ratios are higher in the tidal arm positions of NGC 3256 than in W51, the higher ratios of \(N(X)/N(^{13}\text{CO})\) for most species in NGC 3256 shown in Figures 14 and 15 are due to the variation of \(N(^{13}\text{CO})\), and not \(N(X)\). Further observations are needed to obtain the spatial dependence of \(^{12}\text{C}/^{13}\text{C}\), and we leave it to future work.

5.2. Excitation or Abundance?

From the variation of the column density ratios of molecules with high critical densities over \(^{13}\text{CO}\), we have argued that this variation should be a reflection of multiple components of different excitation conditions within the beam showing as the variation of apparent abundances. However, we cannot exclude the possibility that the intrinsic variation of abundances is playing a role. The molecules we show in Figure 9, HCN, HCO\(^+\), CS, and CN, are theoretically predicted to have a dependence on the temperature, density, and UV or cosmic-ray ionization rate, but it is difficult to think that those molecules all have similar variations among the positions. Therefore, it is more likely that the density distribution function is the largest contributing factor of this variation.
The column density ratios \(N(\text{CH}_3\text{CCH})/N(1^{13}\text{CO})\) do seem to vary as the star formation efficiency, but the behavior of this molecule still needs to be understood.

5.4. Effects of a Merging Event on the Properties of the ISM

From our observations of SiO and CH$_3$OH, it is likely that frequent shocks are occurring in the tidal arms of NGC 3256. Such shocked ISM is also proposed to be present galaxy-wide in NGC 3256 from observations of optical emission lines by 

Rich et al. (2011), and they suggested shocks as an important mechanism to dissipate kinetic energy and angular momentum, which can promote the transport of gas into the central regions. Our observations also suggest a higher fraction of dense clouds in the tidal arms of NGC 3256 than in W51, likely due to the compression from the shock. If such compression occurs, one could ask the question whether this compression can induce star formation by cloud–cloud collision. Judging from the IR observations and the radio recombination line in our observations, there is no such evidence of enhancement. In fact, the positions with a high abundance of shock molecular tracers such as TSE or TSW are the positions that lack evidence of active star formation.

6. Summary

We have conducted a molecular line survey using ALMA Band 3 and Band 6 in an infrared-luminous merger, NGC 3256. This paper first presents continuum images, velocity-integrated intensity maps, and intensity ratio maps. From the observed intensities, the column densities of detected molecules are derived in eight positions of interest, including the two nuclei, the tidal arms positions, and the outflow positions. We have compared the molecular compositions among various positions within NGC 3256, among the nuclei of NGC 3256, Arp 220, and NGC 253, and between the tidal arms of NGC 3256 and a spiral arm in our Galaxy at W51.

Here are our main findings:

1. The intensity ratios HCN(1–0)/HCO$^+$(1–0) and HCN(1–0)/CS(2–1) are lower in the S nucleus than in the N nucleus. The S nucleus has some signs of an AGN while the N nucleus does not have any evidence of an AGN. Previous statistical studies of HCN/HCO$^+$ and HCN/CS in other galaxies showed enhanced ratios in AGN-containing galaxies (Kohno et al. 2001; Imanishi & Nakanishi 2014; Izumi et al. 2016), and our results in NGC 3256 do not follow this trend.

2. Greater influence by shock is found in SiO at the position of the outflow from the souther nucleus of NGC 3256.

3. Comparing the chemistry of NGC 3256, NGC 253, and Arp 220, Arp 220 shows an enhancement in \(N(\text{HC}_3\text{N})/N(1^{13}\text{CO})\) and \(N(\text{SiO})/N(1^{13}\text{CO})\). The enhancement of HC$_3$N is likely to be caused by the hot and dense ISM of Arp 220, while SiO abundances may be increased due to the shock from the outflows.

4. We examined the relationship between the star formation efficiencies and the column density ratios over $^{13}$CO of observed species among the galactic nuclei of NGC 3256, NGC 253, and Arp 220. The only ratio that seems to positively correlate with the star formation efficiency is \(N(\text{CH}_3\text{CCH})/N(1^{13}\text{CO})\). For its explanation, we need more understanding of major formation and destruction routes of CH$_3$CCH.

5.3. Effects of Starburst on the Chemical Composition

If some molecules emit only from compact star-forming regions, then the column densities of these molecules are proportional to the surface number density of the star-forming regions and hence should be proportional to the star formation rate in the observed area. For such molecules, \(N(X)/N(1^{13}\text{CO})\) should be proportional to the star formation efficiencies assuming that \(N(1^{13}\text{CO}) \propto N(\text{H}_2)\). Some column density ratios in Figure 12 are rearranged by the star formation efficiencies in Figure 16. As obviously seen in Figure 16, error bars on the star formation efficiencies are large due to uncertainty in molecular mass. Therefore, the precise relation cannot be determined, but there are some trends that can be discussed as below. Although HC$_3$N and N$_2$H$^+$ are molecules found preferentially in denser regions, those molecules do not have a strong correlation with the star formation efficiency when compared among different galactic nuclei. NGC 3256 has at least a factor of a few, but more likely about an order of magnitude higher, star formation efficiencies than NGC 253, while Arp 220 and NGC 3256 have similar star formation efficiencies. The differences in \(N(\text{HC}_3\text{N})/N(1^{13}\text{CO})\) and \(N(\text{N}_2\text{H}^+)/N(1^{13}\text{CO})\) between the three galactic nuclei are not as large as the variation of star formation efficiency.

There are a few possible reasons for this lack of correlation between the abundances of those molecules and the star formation efficiencies. First, those molecules may not be preferentially in denser regions, those molecules do not have a strong correlation with the surface number density of the star-forming regions. Second, those molecules do not have a strong correlation with the surface number density of the star-forming regions. Therefore, the precise relation cannot be determined, but there are some trends that can be discussed as below. Although HC$_3$N and N$_2$H$^+$ are molecules found preferentially in denser regions, those molecules do not have a strong correlation with the star formation efficiency when compared among different galactic nuclei. NGC 3256 has at least a factor of a few, but more likely about an order of magnitude higher, star formation efficiencies than NGC 253, while Arp 220 and NGC 3256 have similar star formation efficiencies. The differences in \(N(\text{HC}_3\text{N})/N(1^{13}\text{CO})\) and \(N(\text{N}_2\text{H}^+)/N(1^{13}\text{CO})\) among the three galactic nuclei are not as large as the variation of star formation efficiency.
5. The tidal arm positions in NGC 3256 are also strongly influenced by shock compared with the Galactic spiral arm position. They also show hints of compression due to higher apparent column density ratios of molecules with higher critical densities over $^{13}$CO, but these ratios may also be due to lower $^{13}$C elemental abundances.

Our line survey in two frequency bands has highlighted the chemical and physical variation of the ISM within NGC 3256 and among galaxies. Further analysis of the physical conditions such as temperature and density using large velocity gradient analysis would help our understanding of the chemistry. The physics and chemistry of outflow features are worth future follow-up studies.

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References
Aalto, S., Beswick, R., & Jütte, E. 2010, A&A, 522, A59
Aalto, S., García-Burillo, S., Muller, S., et al. 2012, A&A, 537, A44
Aalto, S., García-Burillo, S., Muller, S., et al. 2015a, A&A, 574, A85
Aalto, S., Johansson, L. E. B., Booth, R. S., & Black, J. H. 1991, A&A, 249, 323
Aalto, S., Martín, S., Costagliola, F., et al. 2015b, A&A, 854, A42
Aalto, S., Monje, R., & Martin, S. 2007, A&A, 475, 479
Aalto, S., Polatidis, A. G., Hüttemeister, S., & Curran, S. J. 2002, A&A, 381, 783
Acharyya, K., & Herbst, E. 2016, ApJ, 822, 105
Alef, M. J., Aalto, S., & Wilner, D. J. 2010, ApJ, 723, 104
Alef, M. J., Aalto, S., & Wilner, D. J. 2012, ApJ, 755, 104
Alef, M. J., Walter, F., Bolatto, A. D., et al. 2015, ApJ, 801, 63
Nakajima, H., Takano, S., Kohno, K., et al. 2015, PASJ, 67, 8
Neil, S. G., Ulvestad, J. S., & Campion, S. D. 2003, ApJ, 597, 1043
Nishimura, Y., Watanabe, Y., Harada, N., et al. 2017, ApJ, 848, 17
Ohyama, Y., Terasitama, Y., & Sakamoto, K. 2015, ApJ, 805, 162
Pety, J., Guzmán, V. V., Orkisz, J. H., et al. 2017, A&A, 599, A98
Privon, G. C., Aalto, S., Falstad, N., et al. 2014, ApJL, 797, 90
Sakamoto, K., Aalto, S., Evans, A. S., Wiedner, M. C., & Wilner, D. J. 2010, ApJL, 725, L228
Sakamoto, K., Aalto, S., Wilner, D. J., et al. 2009, ApJL, 700, L104
Sakamoto, K., Ho, P. T. P., Iono, D., et al. 2006a, ApJ, 644, 685
Sakamoto, K., Ho, P. T. P., & Peck, A. B. 2006b, ApJ, 644, 682
Sakamoto, K., Aalto, S., Wilner, D. J., et al. 2010, ApJL, 720, 2101
Saito, T., Iono, D., Espada, D., et al. 2017, ApJ, 834, 6
Sakamoto, K., Aalto, S., Barcos-Muñoz, L., et al. 2017, ApJ, 849, 14
Sakamoto, K., Aalto, S., Combles, F., Evans, A., & Peck, A. 2014, ApJL, 797, 90
Sakamoto, K., Aalto, S., Evans, A. S., Wiedner, M. C., & Wilner, D. J. 2010, ApJL, 725, L228
Sakamoto, K., Aalto, S., Wilner, D. J., et al. 2009, ApJL, 700, L104
Sakamoto, K., Ho, P. T. P., Iono, D., et al. 2006a, ApJ, 636, 685
Sakamoto, K., Ho, P. T. P., & Peck, A. B. 2006b, ApJ, 644, 682
Sanders, D. B., Mazzarella, J. M., Kim, D.-C., Surace, J. A., & Soifer, B. T. 2003, AJ, 126, 1607
Sato, M., Reid, M. J., Brunthaler, A., & Menten, K. M. 2010, ApJ, 720, 1055
Schöier, F. L., van der Tak, F. F. S., van Dishoeck, E. F., & Black, J. H. 2005, A&A, 432, 369
Shirley, Y. L. 2015, PASP, 127, 299
Slonina, E., Wilson, C. D., Aalto, S., & Privon, G. C. 2017, ApJL, 840, L11
Smith, I. W. M., Herbst, E., & Chang, Q. 2004, MNRAS, 350, 323
Sorai, K., Nakai, N., Kuno, N., Nishiyama, K., & Hasegawa, T. 2000, PASJ, 52, 785
Sturm, A., Arvis, L., Surace, J. A., et al. 2013, ApJS, 206, 1
Storm, S., Mundt, L. G., Fernández-López, M., et al. 2014, ApJ, 794, 165
Takano, S., Nakajima, H., Kohno, K., et al. 2014, PASJ, 66, 75
Tully, R. B., Courtois, H. M., Dolphin, A. E., et al. 2013, AJ, 142, 86
Usero, A., García-Burillo, S., Fuente, A., Martín-Pintado, J., & Rodríguez-Fernández, N. J. 2004, A&A, 419, 897
Viti, S., García-Burillo, S., Fuente, A., et al. 2014, A&A, 570, A28
Watanabe, Y., Nishimura, Y., Harada, N., et al. 2017, ApJ, 845, 116
Zinchenko, I., Henkel, C., & Mao, R. Q. 2000, A&A, 361, 1079