DETECTIONS OF C$_2$H, CYCLIC-C$_3$H$_2$, AND H$^{13}$CN IN NGC 1068

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ABSTRACT

We used the Nobeyama 45 m telescope to conduct a spectral line survey in the 3 mm band (85.1–98.4 GHz) toward one of the nearest galaxies with an active galactic nucleus (AGN), NGC 1068, and the prototypical starburst galaxy NGC 253. The beam size of this telescope is $\sim$18$''$, which was sufficient to spatially separate the nuclear molecular emission from the emission of the circumnuclear starburst region in NGC 1068. We detected rotational transitions of C$_2$H, cyclic-C$_3$H$_2$, and H$^{13}$CN in NGC 1068. These are detections of carbon-chain and carbon-ring molecules in NGC 1068. In addition, the C$_2$H $N = 1–0$ lines were detected in NGC 253. The column densities of C$_2$H were determined to be $3.4 \times 10^{15}$ cm$^{-2}$ in NGC 1068 and $1.8 \times 10^{15}$ cm$^{-2}$ in NGC 253. The column densities of cyclic-C$_3$H$_2$ were determined to be $1.7 \times 10^{15}$ cm$^{-2}$ in NGC 1068 and $4.4 \times 10^{15}$ cm$^{-2}$ in NGC 253. We calculated the abundances of these molecules relative to CS for both NGC 1068 and NGC 253, and found that there were no significant differences in the abundances between the two galaxies. This result suggests that the basic carbon-containing molecules are either insusceptible to AGN or are tracing cold ($T_{\text{rot}} \sim 10$ K) molecular gas rather than X-ray irradiated hot gas.

Key words: galaxies: nuclei – ISM: individual objects (NGC 1068, NGC 253) – ISM: molecules – radio lines: galaxies

1. INTRODUCTION

To date, about 40 molecular species have been identified in nearby external galaxies (e.g., list available in CDMS$^5$; Müller et al. 2005). As a result, it is possible to study molecular abundances and chemical reactions in external galaxies. For example, a difference in molecular abundance has been reported between the nearby starburst galaxies NGC 253 and M 82 (e.g., Mauersberger & Henkel 1991; Takano et al. 1995), and the reason for this difference has been discussed. They suggested that the temperature in NGC 253 is higher than that in M 82 and/or that the size of the high-temperature region in NGC 253 is much larger than that in M 82. In addition, Takano et al. (2002) pointed out the peculiarity of the molecular abundance in M 82 among nearby starburst galaxies. Some groups have indicated that the specificity of the molecular abundances of M 82 is because of the chemistry of photon-dominated regions (PDRs; e.g., García-Burillo et al. 2002; Martín et al. 2009).

Different galaxies have different properties and activities. These include those with small or large amounts of gas, having a starburst and/or active galactic nucleus (AGN), and with interaction, etc. Molecular line observations of these different galaxies allow us to study the effects of these different properties/activities on the molecular medium. In fact, some groups have suggested that it is possible to diagnose power sources in dusty galaxies using molecular line ratios (e.g., Kohno et al. 2001, 2008; Usero et al. 2004; Kohno 2005; Inami et al. 2007; Krips et al. 2008). The observation of the molecular gas chemistry of the AGN toward NGC 1068, one of the nearest galaxies with an AGN, has been reported by Usero et al. (2004), Pérez-Beauvittis et al. (2009), and García-Burillo et al. (2010). They observed molecular lines of HCO$^+$, H$^{13}$CO$^+$, SiO, HCO$^+$, HOC$^+$, and CN, and concluded that the circumnuclear disk of NGC 1068 is a giant X-ray-dominated region (XDR). There are theoretical studies on the XDR model by Lepp & Dalgarno (1996), Maloney et al. (1996), Meijerink & Spaans (2005), and Meijerink et al. (2007). However, further systematic observations of molecular lines are indispensable to study the impact of AGN on the interstellar medium. Nevertheless, no systematic unbiased scans of millimeter/submillimeter molecular lines toward AGN have been published to date, although such scans do exist for two nearby starburst galaxies (NGC 253, Martín et al. 2006; M 82, Naylor et al. 2010). Therefore, we started a project to conduct a line survey in the 3 mm band of NGC 1068 using the 45 m telescope at Nobeyama Radio Observatory (NRO) in Japan. The beam size of this telescope (18$''$ at 86 GHz) is smaller than the size of the circumnuclear starburst ring in NGC 1068 ($d \sim 30''$; e.g., Planesas et al. 1991), and it is therefore essential to the study of the impact of the AGN on the surrounding molecules; this will enable us to mitigate the contamination of the molecular lines from the circumnuclear starburst region in NGC 1068. We also observed NGC 253 to compare the effects of AGN on molecular abundance. This is an ongoing project, and we present here the initial results of the survey.

In this study, we report detections of the rotational transition lines of C$_2$H, cyclic-C$_3$H$_2$, and H$^{13}$CN in NGC 1068, and detection of the C$_2$H $N = 1–0$ transition in NGC 253 as well as other previously reported lines.

The C$_2$H molecule was first detected in interstellar clouds by Tucker et al. (1974). However, extragalactic detections are limited to just a few objects (M 82, Henkel et al. 1988; NGC 4945, Henkel et al. 1990; NGC 253, Martín et al. 2006). The C$_2$H molecule is important to study the formation and the characteristics of carbon-chain molecules, because it is related to the carbon-chain growth. The cyclic-C$_3$H$_2$ molecule has been...
observed in a large number of galactic sources. In external galaxies, it has been detected in Cen A (Seaquist & Bell 1986; Bell & Seaquist 1988); NGC 253, and M 82 (Mauersberger et al. 1991). Information on the abundances of basic carbon-containing molecules is important for understanding the carbon chemistry in NGC 1068. The detection of H^{13}CN in the external galaxies has only been reported toward NGC 253 by Mauersberger & Henkel (1991). It is interesting that the isotope of HCN was detected in NGC 1068, because the isotope ratio gives the constraint on the optical depth of the HCN line; this will help us to unfold the nature of the overabundant HCN emission at the center of NGC 1068.

2. OBSERVATIONS

The observations at the 3 mm region (85.1–98.4 GHz) toward NGC 1068 and NGC 253 were carried out from 2009 February to May and from 2010 January to May using the 45 m telescope. The total observational times under good weather condition are 44.5 and 22.5 hr for NGC 1068 and NGC 253, respectively. The adopted central position and the systemic velocity (\(v_{SR}\)) of NGC 1068 are \(\alpha J_{2000} = 02h42m40s798, \delta J_{2000} = -00o047\rangle938\) and 1150 km s\(^{-1}\) respectively (Schinnerer et al. 2000). Similarly, the adopted central position and \(v_{SR}\) of NGC 253 are \(\alpha J_{2000} = 00\rangle047\rangle33\rangle0\) and \(v_{SR} = -25\rangle17\rangle23\rangle0\) (Martin et al. 2006) and 230 km s\(^{-1}\) (Takano et al. 1995), respectively. In particular, we focused on the cyclic-\(C_3H_2\) J_{2−1} K=1,=2,1−0 (\(v_{rest} = 85.338906\) GHz), H^{13}CN J = 1−0 (\(v_{rest} = 86.390167\) GHz, F = 2−1), \(C_2H\) N = 1−0 (\(v_{rest} = 87.316925\) GHz, J = 3/2−1/2, F = 2−1), HCN J = 1−0 (\(v_{rest} = 88.631847\) GHz, F = 2−1), \(CH_3OH\), F = 2−1, \(K = 2\rangleK = 1\rangleK (v_{rest} = 96.741377\) GHz, J = 2−1−0 \(A^\prime\)), and CS J = 2−1 (\(v_{rest} = 97.980953\) GHz) transitions. These rest frequencies were taken from the database of Lovas (2004).

The dual-polarization sideband-separating receiver (Nakajima et al. 2008) was used with typical system noise temperatures including an atmosphere of about 150–300 K, and the image rejection ratio (IRR) was typically better than 10 dB. It was checked by the IRR measurement system (Nakajima et al. 2010), which employs an artificial signal injection from the top of the receiver optics. The half-power beam widths (HPBWs) at 86 GHz were 18:3 and 18:4 for H-polarization (H-pol.) and V-polarization (V-pol.), respectively, in 2009, and 19:2 and 18:9 for H-pol. and V-pol., respectively, in 2010. The measured main-beam efficiencies (\(\eta_{mb}\)) were 0.43 ± 0.02 and 0.42 ± 0.02 for H-pol. and V-pol., respectively, in 2009, and 0.49 ± 0.04 and 0.47 ± 0.03 for H-pol. and V-pol., respectively, in 2010. The backend used consisted of eight digital spectrometers (Sorai et al. 2000), each having a bandwidth of 512 MHz and a resolution of 605 kHz. We used four spectrometers for each polarization, lined up in the direction of frequency.

The line intensities were calibrated by the chopper wheel method. The telescope pointing was checked by observing the nearby SIO maser sources, o-Cet for NGC 1068 and R-Aqr for NGC 253, every ~1.5 hr. The pointing accuracy was better than about 5\''. The position-switching mode was employed for the observations where the reference position was taken at the position with an azimuthal angle difference of +5\'' for both galaxies. The integration time on each position was 20 s.

3. RESULTS

The main results include detections of \(C_2H\), cyclic-\(C_3H_2\), and H^{13}CN toward NGC 1068 and the \(C_2H\) N = 1−0 transition toward NGC 253. In addition, we observed the HCN J = 1−0 line and marginally detected \(CH_3OH\) (J = 2−1−1K) toward NGC 1068. Very recently, García-Burillo et al. (2010) reported the detection of the \(CH_3OH\) group of transitions (J = 2−1−1K and J = 3−2−2K). Moreover, detection of CS (J = 2−1) has already been reported by Tacconi et al. (1997). Nonetheless, we detected this transition in NGC 1068 using a single dish telescope. Figures 1 and 2 show the observed line profiles, and Table 1 summarizes the parameters derived from the Gaussian fits to the observed lines.

3.1. \(C_2H\)

The \(C_2H\) N = 1−0 line consists of six hyperfine components (J = 3/2−1/2, F = 1−1, F = 2−2, F = 1−0 and J = 1/2−1/2, F = 1−1, F = 0−0, F = 1−0). We detected two fine structure components because of the line blending. Thus, the fitting has been carried out with a comb of Gaussian profiles at the rest frequencies of the hyperfine components (Gottlieb et al. 1983) using the same widths and with fixed optical depth (\(\tau\)) ratios relative to the main component based on the theoretical relative intensities (Tucker et al. 1974). The width of the components and the optical depth were taken as free parameters.

The main-beam brightness temperature (\(T_{mb}\)) can be calculated from the following equation:

\[
T_{mb} = \eta_{mb} [J(T_{ex}) - J(T_{bg})] (1 - e^{-\tau}),
\]

where

\[
J(T) = \frac{h \nu}{k} \times \frac{1}{\exp\left(\frac{h \nu}{k T_{ex}} - 1\right)}.
\]

The beam filling factor, \(\eta_{fill} = \frac{\theta_{beam}^2}{(\theta_1^2 + \theta_2^2)}\), accounts for the dilution effect due to the coupling between the source and the telescope beam in the approximation of a Gaussian source distribution of size \(\theta_1\) (FWHM) that is observed with a Gaussian
beam size $\theta_b$ (HPBW). The adopted $\theta_b$ of NGC 1068 is 4", which is assumed from the distribution of HCN (Heller & Blitz 1995; Krips et al. 2008). The adopted $\theta_b$ of NGC 253 is 20", which is assumed from the distribution of CS (Martín et al. 2006). We observed the C$_2$H lines only in 2009, and $\theta_b$ was measured to be $\sim$ 18':4 at 86 GHz in 2009. Thus, for the C$_2$H observation, the values of $\eta_{mb}$ for NGC 1068 and NGC 253 with the 45 m telescope are 0.045 and 0.54, respectively. We assumed the excitation temperatures ($T_{ex}$) toward NGC 1068 to be 7.6 K, which is derived from the analysis of the rotation diagram of the CS lines (see Section 3.3), and that toward NGC 253 to be 5.8 K, which is derived from the analysis of the rotation diagram of the C$_2$H lines (see the paragraph after next). The employed cosmic background radiation ($T_{bg}$) is 2.7 K. The fitting results were overlaid on the spectra (Figures 2(a) and (b)). The Gaussian profiles for C$_2$H in NGC 253 do not reproduce the observed spectrum well. The peak position of the main component seems to be shifted possibly because of the self-absorption effect. Because of this shift, the overall fitting results are not as good as those of NGC 1068.

We obtained the optical depth of the C$_2$H main component ($N = 1-0, J = 3/2-1/2, F = 2-1$) of NGC 1068 and NGC 253 to be 0.06 and 0.05, respectively. The total of the optical depth of all the C$_2$H components in both galaxies are 0.15 and 0.13, respectively. This indicates that the C$_2$H $N = 1-0$ lines have small ($\leq 1$) optical depth in NGC 1068 and NGC 253. If the source size of NGC 1068 is changed to 10", to be able to see the effect of the assumed source size, then $T_{ex}$ becomes 8.5 K. In this case, the optical depth is calculated to be 0.01. Therefore, the result of the small optical depth of C$_2$H is rather robust considering the uncertainty of the assumed source size. The obtained column densities of C$_2$H in NGC 1068 and NGC 253 are $3.4 \times 10^{15} \text{cm}^{-2}$ and $1.8 \times 10^{15} \text{cm}^{-2}$, respectively.

For this calculation, we adopted a dipole moment of 0.8 debye (Tucker et al. 1974). On the other hand, the column density of 1.2 $\times 10^{15}$ cm$^{-2}$ was reported in NGC 253 from the C$_2$H $N = 2-1$ line by Martín et al. (2006). Thus, our result compares well to theirs.

Because the C$_2$H $N = 2-1$ line was observed by Martín et al. (2006), we made a rotational diagram of C$_2$H toward NGC 253 (Figure 3). We adopted the basic equation for the rotation diagram (e.g., Turner 1991). The fit to the $N = 1-0$ (this work) and 2–1 (Martín et al. 2006) transitions of C$_2$H toward NGC 253 appears to indicate a low-excitation gas of $5.8_{-0.7}^{+0.5}$ K. This value is close to the $T_{rot}$ of NO (6 K) and NS (7 K), which are reported by Martín et al. (2006). These molecular lines trace gas of a low-temperature component.

### 3.2. Cyclic-C$_3$H$_2$

Spectra of cyclic-C$_3$H$_2$ are shown in Figures 2(c) and (d) for NGC 1068 and NGC 253, respectively. The 2$_{1,2}$–1$_{0,1}$ transition was clearly detected in both galaxies. Figure 3 shows the rotational diagram toward NGC 253, where we employed the dipole moment of 3.43 debye reported by Kanata et al. (1987) (Brown et al. 1987 reported it to be 3.32 debye). The statistical weight is 3 for the ortho levels and 1 for the para levels due to two equivalent hydrogen nuclei. In this diagram, we assumed an ortho-to-para ratio of 3. The fit to the 2$_{1,2}$–1$_{0,1}$ (ortho; this work) and 3$_{2,2}$–2$_{1,1}$ (para; Martín et al. 2006) transitions of cyclic-C$_3$H$_2$ toward NGC 253 appears to indicate a low-excitation gas with $T_{rot}$ of $7.6_{-1.3}^{+1.5}$ K. Martín et al. (2006) detected three transitions of the cyclic-C$_3$H$_2$ lines and obtained $T_{rot}$ of 9 $\pm$ 8 K from their rotational diagram. However, they reported that the lines are blended with other lines except the 3$_{2,2}$–2$_{1,1}$ transition. This is the reason why we used only their 3$_{2,2}$–2$_{1,1}$ transition in our rotation diagram. As a result, a more probable $T_{rot}$ was obtained. The column density of cyclic-C$_3$H$_2$ toward NGC 253 is derived using the value of the intersection of the linear regression with the y-axis of Figure 3 and the partition

### Table 1

| Line         | Transition | $\int T_{mb}dV$ (mK km s$^{-1}$) | $T_{mb}$ (mK) | $V_{LSR}$ (km s$^{-1}$) | $\Delta v$(FWHM) (km s$^{-1}$) | $rms$ ($T_{mb}$) (mK) |
|--------------|------------|---------------------------------|---------------|------------------------|--------------------------|----------------------|
| NGC 1068     | Cyclic-C$_2$H$_2$ $J_{Ka,Kc} = 2_{1,2}$–$1_{0,1}$ | 1200            | 5             | 1148                   | 248                      | 1.7                   |
|              | H$_{13}$CN | $J = 1$–0                      | 1900          | 9                      | 1111                    | 234                   | 4.1                   |
|              | C$_2$H     | $N = 1$–0                      | 6900          | 19                     | 1139                    | 209                   | 3.3                   |
|              | HCN        | $J = 1$–0                      | 35000         | 128                    | 1117                    | 336                   | 19.1                  |
|              | CH$_3$OH   | $J = 2K - 1K$                 | 1500          | 7                      | 1104                    | 235                   | 3.8                   |
|              | CS         | $J = 2$–1                      | 6400          | 30                     | 1174                    | 312                   | 4.8                   |
| NGC 253     | Cyclic-C$_2$H$_2$ $J_{Ka,Kc} = 2_{1,2}$–$1_{0,1}$ | 5500            | 30            | 272                    | 243                      | 4.6                   |
|              | C$_2$H     | $N = 1$–0                      | 48000         | 129                    | 219                     | 199                   | 9.1                   |
function of cyclic-C_3H_2 at 7.6 K. For the calculation of the partition function, the energy levels in Vrtilek et al. (1987) were used. The obtained column density is 4.4 x 10^{13} \text{cm}^{-2}. For NGC 1068, the obtained column densities are 1.7 x 10^{13} \text{cm}^{-2} (\theta_{s} = 4') and 1.8 x 10^{13} \text{cm}^{-2} (\theta_{s} = 10'). These column densities in NGC 1068 were derived from the above analysis of the rotation diagram assuming \( T_{\text{rot}} \) of 7.6 K, which is derived from the rotation diagram of CS (Section 3.3).

3.3. CS

Figure 1(d) shows the CS \( J = 2-1 \) spectrum toward NGC 1068. In addition, the CS \( J = 3-2, 5-4, \) and 7–6 transitions have already been reported by Bayet et al. (2009) in NGC 1068. Using these four lines and assuming \( \theta_{s} \) of 4', the rotational temperature was calculated to be 12.6 K from the rotation diagram as inducted by a dashed line (Figure 3). However, Bayet et al. mentioned that the \( J = 7-6 \) line is marginally detected. Subsequently, with the exception of the \( J = 7-6 \) line, the performed fits are shown by the thin solid line in Figure 3, and the obtained \( T_{\text{rot}} \) is 7.6 K. The result of the fitting, excluding the \( J = 7-6 \) line, is deemed appropriate, because the fitting error is significantly small. If the \( \theta_{s} \) of NGC 1068 is changed to 10', then the \( T_{\text{rot}} \) will be 13.0 K and 8.5 K (excluding the \( J = 7-6 \) line). We find that the slope of the linear regression in the CS rotational diagram with our new data point is still consistent with previous results (Bayet et al. 2009), indicating that physical properties of the gas traced by CS (\( J = 2-1 \)) are similar to those traced by the higher \( J \) transitions of CS. \( T_{\text{rot}} \) of 7.1 K (excluding the \( J = 7-6 \) line) has been reported by Bayet et al. (2009), and our result is consistent with their result.

3.4. HCN and H^{13}CN

The relative intensities of the H^{13}CN (Figure 1(a)) and HCN (Figure 1(b)) lines can be used as a measure of the optical depth of HCN. The optical depth is derived using the following equation, assuming the same excitation temperature for HCN and H^{13}CN, and an \(^{12}\text{C}/^{13}\text{C} \) isotopic ratio of 50 (Lucas & Liszt 1998):

\[
T_{A}^{\text{H^{13}CN}}(J = 1-0) = \frac{1}{1 - e^{-\tau_{\text{HCN}}}}.
\]

We obtained an optical depth of about 2.6 for the HCN \( J = 1-0 \) line toward NGC 1068. Thus, the HCN \( J = 1-0 \) line in NGC 1068 is optically thick.

4. DISCUSSION

It is interesting to examine the effects of an AGN on molecular abundance. For example, is there a significant difference in the molecular abundance in circumnuclear disk because of the presence of an AGN? Here, we focused on the C_2H and cyclic-C_3H_2 molecules that were detected in this study toward NGC 1068. The relative abundances of C_2H were calculated with respect to CS in both galaxies to study the effects of the AGNs. CS was employed to calculate the relative abundances because the multi-transition data of CS lines have been published (Bayet et al. 2009). In addition, the critical density of CS is about \( 10^{4}-10^{5} \text{cm}^{-3} \), and it traces the region where the densities are higher than that traced by CO. The column densities of CS toward NGC 1068 and NGC 253 were obtained as reported in Section 3.3.

For C_2H, we obtained the abundances relative to CS of 5.5 (\( \theta_{s} = 4' \)) and 5.7 (\( \theta_{s} = 10' \)) in NGC 1068, and of 4.3 in NGC 253. For cyclic-C_3H_2, we obtained the abundances relative to CS of 0.03 (\( \theta_{s} = 4' \)) and 0.16 (\( \theta_{s} = 10' \)) in NGC 1068, and of 0.10 in NGC 253. Martin et al. (2006) reported the column density in NGC 253 to be \( 3.0 \times 10^{14} \text{cm}^{-2} \), and a relative abundance calculated to be 0.07 in the same way as shown above. It is almost equal in ratio for both of the molecules, and we found no significant differences in the relative abundances of NGC 1068 and NGC 253. Thus, there is a possibility that these basic carbon-containing molecules are insusceptible to AGNs. Another possibility is that C_2H and cyclic-C_3H_2 mainly exist in an extended gas away from the AGN, because the rotation temperature of C_2H (7.6 K) is lower than the kinetic temperature of the gas around the central few hundred parsecs (\( \geq 70 \text{K} \); Tacconi et al. 1994). However, as far as we know, there is no theoretical study on C_2H and cyclic-C_3H_2 in XDR. Therefore, such model calculations are essential.

5. CONCLUSIONS

We started line surveys in the 3 mm band toward NGC 1068 and NGC 253. The main results include detections of C_2H, cyclic-C_3H_2, and H^{13}CN toward NGC 1068 and the C_2H \( N = 1-0 \) transition toward NGC 253. We calculated the relative abundances of C_2H and cyclic-C_3H_2 with respect to CS in both galaxies and found no significant differences in the results between NGC 1068 and NGC 253. Thus, it is concluded that these basic carbon-containing molecules are insusceptible to AGNs and/or these molecules exist in a cold gas away from an AGN.

We continue an unbiased line survey toward NGC 1068 and NGC 253 and examine the abundances of other molecules in order to study the effects of AGNs on the interstellar medium. A clear separation of the circumnuclear disk from the starburst ring is important for understanding the abundances of the molecular gas around AGNs. With the advent of ALMA, we will be able to study the AGN chemistry with much higher spatial resolution.
This work is based on observations with the NRO 45 m telescope, as a part of the line surveys of the legacy projects. The authors thank the project members for helpful discussion. We also thank all of the staff of the 45 m telescope for their support. We are also grateful to Ryohei Kawabe for his advice and support to the line survey project.

Note added in proof. After the submission of this paper, we found two relevant papers. Snell et al. (2011) detected C$_2$H in NGC 1068. Costagliola et al. (2011) detected C$_2$H and H$^{13}$CN in NGC 1068.

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