Distributions of molecules in the circumnuclear disk and surrounding starburst ring in the Seyfert galaxy NGC 1068 observed with ALMA

Shuro TAKANO,1,2,* Taku NAKAJIMA,3 Kotaro KOHNO,4,5 Nanase HARADA,6 Eric HERBST,7 Yoichi TAMURA,4 Takuma IZUMI,4 Akio TANIGUCHI,4 and Tomoka TOSAKI8

1Nobeyama Radio Observatory, Nobeyama, Minamimaki, Minamisaku, Nagano 384-1305, Japan
2Department of Astronomical Science, The Graduate University for Advanced Studies (Sokendai), Nobeyama, Minamimaki, Minamisaku, Nagano 384-1305, Japan
3The Solar-Terrestrial Environment Laboratory, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8601, Japan
4Institute of Astronomy, The University of Tokyo, 2-21-1 Osawa, Mitaka, Tokyo 181-0015, Japan
5Research Center for Early Universe, School of Science, The University of Tokyo, 7-3-1 Hongo, Bunkyo, Tokyo 113-0033, Japan
6Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, D-53121 Bonn, Germany
7Department of Chemistry, University of Virginia, McCormick Road, PO Box 400319, Charlottesville, VA 22904, USA
8Joetsu University of Education, Yamayashiki-machi, Joetsu, Niigata 943-8512, Japan

*E-mail: takano.shuro@nao.ac.jp

Received 2013 July 26; Accepted 2014 May 14

Abstract

Sensitive observations with the Atacama Large Millimeter/submillimeter Array (ALMA) allow astronomers to observe the detailed distributions of molecules with relatively weak intensity in nearby galaxies. In particular, we report distributions of several molecular transitions including shock and dust related species (\(^{13}\)CO \(J = 1-0\), \(^{18}\)O \(J = 1-0\), \(^{13}\)CN \(N = 1-0\), CS \(J = 2-1\), SO \(J_N = 3_{2-21}\), HNCO \(J_k,\kappa = 5_{0,5-4_{0,4}}\), \(^{3}\)HC\(_3\)N \(J = 11-10, 12-11\), \(^{3}\)CH\(_3\)OH \(J_{K} = 2_{K-1_{K}}\), and \(^{3}\)CH\(_3\)CN \(J_{K} = 6_{K-5_{K}}\)) in the nearby Seyfert 2 galaxy NGC 1068 observed with the ALMA early science program. The central \(\sim 1'(\sim 4.3\) kpc) of this galaxy was observed in the 100-GHz region covering \(\sim 96-100\) GHz with an angular resolution of \(\sim 4'' \times 2'' \) (290 pc \(\times 140\) pc) to study the effects of an active galactic nucleus and its surrounding starburst ring on molecular abundances. Here, we present images and report a classification of molecular distributions into three main categories: (1) molecules concentrated in the circumnuclear disk (CND) (SO \(J_N = 3_{2-21}\), \(^{3}\)HC\(_3\)N \(J = 11-10, 12-11\), and \(^{3}\)CH\(_3\)CN \(J_{K} = 6_{K-5_{K}}\)), (2) molecules distributed both in the CND and the starburst ring (CS \(J = 2-1\) and \(^{3}\)CH\(_3\)OH \(J_{K} = 2_{K-1_{K}}\)), and (3) molecules distributed mainly in the starburst ring (\(^{13}\)CO \(J = 1-0\) and \(^{18}\)O \(J = 1-0\)). Since most of the molecules such as \(^{3}\)HC\(_3\)N observed in the CND are easily dissociated by UV photons and X-rays, our results indicate that these molecules must be effectively...
shielded. In the starburst ring, the relative intensity of methanol at each clumpy region is not consistent with those of $^{13}$CO, C$^{18}$O, or CS. This difference is probably caused by the unique formation and destruction mechanisms of CH$_3$OH.

**Key words:** line: identification — galaxies: individual (NGC 1068) — galaxies: Seyfert — galaxies: starburst — radio lines: galaxies

### 1 Introduction

Recent rapid advances in millimeter/submillimeter (mm/submm) receivers equipped with wide-band spectroscopic capabilities, such as EMIR (Eight Mixer Receiver) with the WILMA (Wideband Line Multiple Autocorrelator) spectrometer on the IRAM (Institut de Radioastronomie Millimétrique) 30-m telescope (Carter et al. 2012), Z-Spec on the CSO (Caltech Submillimeter Observatory) 10.4-m telescope (Bradford et al. 2004), the Redshift-search-receiver on the LMT (Large Millimeter Telescope) 50-m (Erickson et al. 2007), TZ with the SAM45 (Spectral Analysis Machine for the 45m telescope) spectrometer on the NRO (Nobeyama Radio Observatory) 45-m telescope (Iono et al. 2012; Nakajima et al. 2013), and SPIRE-FTS (Spectral and Photometric Imaging Receiver-Fourier Transform Spectrometer) on Herschel (Griffin et al. 2010), have revolutionized our view concerning chemical properties in galaxies. Unbiased spectral line surveys toward various types of galaxies have been conducted (e.g., Martin et al. 2006; Naylor et al. 2010; van der Werf et al. 2010; Snell et al. 2011; Costagliola et al. 2011; Nakajima et al. 2011; Martin et al. 2011; Kamenetzky et al. 2011; Rangwala et al. 2011; Aladro et al. 2011, 2013), revealing the richness and diversity of spectral line features.

These chemical properties have been expected to be powerful astrophysical tools for the study of galaxies, because activity in the central regions of galaxies, such as a burst of massive star-formation or an active galactic nucleus (AGN), must have a strong impact on the chemical and physical properties of the surrounding interstellar medium (ISM). For instance, elevated HCN emission with respect to CO and/or HCO$^+$ has often been detected toward AGNs (e.g., Jackson et al. 1993; Tacconi et al. 1994; Helfer & Blitz 1995; Kohno et al. 1996, 2003; Krips et al. 2007, 2008; Krips 2012; Izumi et al. 2013), where it is expected to be the imprint of either strong X-ray irradiation/ionization (Usero et al. 2004; García-Burillo et al. 2010; Davies et al. 2012) and/or a high-temperature environment caused by AGN activity (e.g., Harada et al. 2010; Izumi et al. 2013). Nevertheless, some controversial observational results (e.g., Baan et al. 2008; Snell et al. 2011; Costagliola et al. 2011; Sani et al. 2012) and theoretical work on the physical and chemical properties of the ISM in external galaxies (e.g., Meijerink & Spaans 2003; Meijerink et al. 2007), which are somewhat inconsistent with the idea of the enhanced HCN emission among AGNs, suggest that our current understanding of physical and chemical properties in galaxies is still far from complete.

One of the promising directions for study is to build detailed inventories of spectral lines in the vicinity of AGNs. By comparing them with the results of spectral line surveys in the central regions of starburst galaxies such as NGC 253 (e.g., Martin et al. 2006) and M 82 (e.g., Aladro et al. 2011), we can identify the key combinations of molecules that differentiate the power sources in galaxies. For this purpose, the circumnuclear disk (CND: e.g., Usero et al. 2004) of NGC 1068 is one of the best targets, although NGC 1068 is known to host intense starburst regions along the inner spiral arms or ring (e.g., Telesco & Decher 1988). Since the diameter of the starburst ring is fairly large (≈30′′), the emission from the CND (<4′′) can be easily separated spatially, if we employ mm/submm interferometers. Note that little if any signature for recent nuclear starburst activity has been identified in the central region of NGC 1068 (e.g., Imanishi et al. 1997; Cid Fernandes et al. 2001; Davies et al. 2007), despite the fact that the CND is bright in $^{12}$CO (J = 3–2) and other molecular lines (e.g., Schinnerer et al. 2000; Tsai et al. 2012). This makes the CND of NGC 1068 ideal for the study of the AGN imprints, because nuclear starbursts often cohabit with AGNs (e.g., Imanishi & Wada 2004), hampering clear separation of spectral line features between starbursts and AGNs.

To date, several unbiased line surveys at mm/submm wavelengths have been reported towards the center of NGC 1068 (Snell et al. 2011; Costagliola et al. 2011; Kamenetzky et al. 2011; Spinoglio et al. 2012; Aladro et al. 2013) using single-dish telescopes, but contamination from starbursts associated with inner spiral arms/ring could be a problem if we consider the sizes of the observing beams (14′′–70′′). On the other hand, interferometric imaging of the CND gives clean measurements of spectral lines, but the observed lines are limited to major species such as CO, HCN, HCO$^+$, CS, CN, and SiO (e.g., Papadopoulos et al. 1996; Tacconi et al. 1997; Kohno et al. 2008; García-Burillo et al. 2010; Krips et al. 2011) due to the
limitation in sensitivity of the existing pre-ALMA mm/submm arrays.

In this situation, we proposed to observe several interesting molecules simultaneously in the 98- and 110-GHz regions sensitively with ALMA. These frequency regions are rich in molecules, including typical shock/dust related species and the CO isotopologues. We first obtained the intensities of such lines based on our line survey project with the 45-m telescope (Nakajima et al. 2011). As an additional advantage of this frequency region, the primary beams of the ALMA 12-m antennas (~1°) cover both the CND and the starburst ring in one field of view, which is useful for our purposes.

In this paper, we report a high-resolution imaging study of molecular lines in the central region (~1°) of NGC 1068 observed with ALMA. Even in its early science operation phase, ALMA is already powerful enough to simultaneously observe 10 lines from nine molecules (\(^{13}\)CO)\(_{J = 1-0}\), \(^{18}\)OJ \(_{J = 1-0}\), \(^{13}\)CN\(_{J = 1-0}\), CSJ \(_{J = 2-1}\), SO\(_{J = 3-2}\), HNCO\(_{J_{K_a,K_c} = 5,0,5-4,0,4}\), HCNJ \(_{J = 11-10}\), 12–11, CH\(_3\)OHJ \(_{K = 2-1,K}\), and CH\(_3\)CN\(_{J_K = 6,5-5,5}\)) within a frequency coverage of ~7.0 GHz at the 3-mm band, uncovering a wide variety of molecular line distributions. We describe our observations and data reduction in section 2, and present the images and spectra of the observed molecular lines in section 3. In section 4, the molecular distributions will be classified into three main categories: (1) molecules concentrated in the CND, (2) molecules distributed both in the CND and the starburst ring, and (3) molecules distributed mainly in the starburst ring. Some implications of this diversity are also discussed in that section. Throughout the paper, we assume that the distance of NGC 1068 is 14.4 Mpc (Tully 1988; Bland-Hawthorn et al. 1997); at this distance, 1° corresponds to 72 pc.

2 Observations and data reduction

The observations were carried out with ALMA in the early science program (cycle 0) in 2012 January. The receivers in band 3 (100-GHz region) were used. The 16 antennas available were in the compact configuration. The adopted central position of NGC 1068 was RA(J2000.0) = \(2^\text{h}42^\text{m}40^\text{s}798\) and Dec(J2000.0) = \(-00^\circ00'47"938\). The systemic velocity employed was 1150 km s\(^{-1}\). The position and the velocity were taken from Schinnerer et al. (2000). This position is the radio core at the AGN observed with MERLIN (The Multi-Element Radio Linked Interferometer Network) at 5 GHz (Muxlow et al. 1996).

As a correlator set-up, the two spectral windows were placed in the lower sideband (LSB: covering ~96–100 GHz), and the other two were placed in the upper sideband (USB: covering ~108–111 GHz). Each spectral window covered 1875 MHz with 3840 channels resulting in a frequency resolution of 488 kHz. Such a set-up efficiently covered frequency regions with rich spectral lines, as mentioned in the Introduction. The final results were presented with the velocity resolution of ~19 km s\(^{-1}\) (at 100 GHz) to improve the signal-to-noise ratio.

The total observational time was about 110 minutes including calibration and overheads. The spatial resolution of the observations was 4.2' × 2.4' (~300 pc × 170 pc) at the principal axis of 176° in the spectral window of the lowest frequency. The system temperature was ~53–133 K depending on frequency and antennas. The achieved noise level (rms) was ~1.1–1.7 mJy beam\(^{-1}\) depending on the spectral window and image region. The observational parameters are summarized in table 1.

The data were reduced with the reduction software CASA (mainly with ver. 3.4). We used continuum subtracted calibrated data (measurement set) and image cubes provided by the ALMA Regional Center. For molecular lines with no provided image cubes (\(^{13}\)CN, HNCO, and CH\(_3\)CN), we obtained images from the measurement set above. The images of integrated intensity (moment 0 maps) were made using pixels with all flux values in the image cubes.

3 Results

3.1 Overview of the images

Thanks to the high sensitivity of ALMA, all expected lines were detected with a short observational time. The integrated intensity images are shown in figures 1 and 2. In figure 1 images with a significant distribution in the starburst ring are shown. These images are from the \(^{13}\)CO\(_{J = 1-0}\), \(^{18}\)OJ \(_{J = 1-0}\), CSJ \(_{J = 2-1}\), and CH\(_3\)OHJ \(_{K = 2-1,K}\) rotational transitions.

1. \(^{13}\)CO and \(^{18}\)O: The images of these CO isotopic species show rather weak signals in the CND, but show clear distributions in the starburst ring. In particular, a south-west region in the starburst ring shows the strongest emission. These overall pictures agree well with the past interferometric \(^{13}\)CO (J = 1–0) images (e.g., Helfer & Blitz 1995; Papadopoulos et al. 1996; Tacconi et al. 1997), but the quality of the image is greatly improved with ALMA. The clear distributions in the starburst ring are also qualitatively similar to those of the \(^{12}\)CO \(_{J = 1-0}\) and 3–2 transitions (e.g., Schinnerer et al. 2000; Tsai et al. 2012), but the emission in the CND is clearly seen in these \(^{12}\)CO images. The difference in the emission in the CND between
Table 1. Observational parameters (ALMA Band 3, cycle 0).

| Parameter                                | Value                                                                 |
|-------------------------------------------|-----------------------------------------------------------------------|
| Date                                      | 2012 January 9 and 10                                                 |
| Number of antennas                        | 16                                                                   |
| Configuration                             | Compact                                                              |
| Phase center (Schinnerer et al. 2000)     | RA (J2000.0) = 2^h 42^m 40.798, Dec (J2000.0) = −00° 00′ 47″ 938   |
| Bandpass calibrator                       | J0423−013                                                           |
| Flux calibrator                           | Callisto                                                             |
| Phase calibrator                          | J0339−017                                                           |
| Central frequency (GHz) and beam size with | 97.38 (LSB, spw0), 4′ 2 × 2′ 4 176°                                 |
| its principal axis of each spectral window| 99.3875 (LSB, spw1), 4′ 2 × 2′ 2 178°                               |
| Frequency resolution (kHz)                | 488                                                                  |
| Velocity resolution (km s\(^{-1}\))       | ~ 19.0 at 100 GHz (13 channel binning)                              |
| Rms noise (mJy beam\(^{-1}\))             | ~ 1.1–1.7                                                            |

\(^{12}\)CO and our CO isotopic species indicates that the CO \(J = 1–0\) emission in the CND is optically thinner than that in the starburst ring. A quantitative analysis has been done with the ALMA band 7 data (~ 330-GHz region) by Nakajima et al. (2014) and A. Taniguchi et al. (in preparation). Next, the total flux ratio of the CO isotopic species \((^{18}\)O/\(^{12}\)CO) was calculated, and the obtained value is ~ 0.34. This ratio is similar to the corresponding ratio of 0.3 from past interferometric data using the OVRO (Owens Valley Radio Observatory) mm-array (Papadopoulos et al. 1996) and the value of 0.28 calculated from line survey data with the IRAM 30-m telescope (Aladro et al. 2013). In addition, we are investigating the properties of giant molecular associations based on the \(^{13}\)CO, \(^{18}\)O, CS, and \(\mathrm{CH}_3\)OH lines with data cubes of high spectral resolution produced from the same data of band 3. The relation to the star-formation rate (SFR) is also being investigated. The results will be published separately (T. Tosaki et al. in preparation).

2. CS: The strong emission is concentrated in the CND, while weak emission is seen in the starburst ring. This is in sharp contrast to the distributions of the CO isotopic species. Since CS is a typical high-density tracer, the CS distributed area should have a relatively high density in the first-order approximation. In the starburst ring, the CS emission is relatively strong in the south-western region. This pattern is the same as the distributions of the CO isotopic species in the starburst ring. A CS \(J = 2–1\) image was also reported by Tacconi et al. (1997); these authors used the IRAM Plateau de Bure interferometer. Their results also show the central concentration and additional clumpy features in the starburst ring.

3. \(\mathrm{CH}_3\)OH: Our data yield the first interferometric image in NGC 1068. Methanol is distributed both in the CND and in the starburst ring with similar intensity. Although the signal-to-noise ratio is not high enough, methanol is probably distributed both in the east and west knots (Schinnerer et al. 2000) in the CND. The distribution in the starburst ring is similar to those of \(^{13}\)CO, \(^{18}\)O, and CS on the whole, but the relative intensity of methanol at each clumpy region is not as consistent with those of \(^{12}\)CO, \(^{18}\)O, and CS. In particular, a striking difference can be seen in the eastern region, where methanol emission is the strongest, although the intensities of the CO isotopic species and CS are relatively weak. Methanol is thought to be produced on grain surfaces (e.g., Watanabe & Kouchi 2002) and sublimed into the gas-phase by star-formation activities. This interesting distribution of methanol and its relation to star formation will be discussed later.

In figure 2, images exhibiting concentrated distributions in the CND are shown. These images involve rotational lines of the following transitions: \(^{13}\)CN \(N = 1–0\), SO \(N = 3–2\), HNCO \(J_{K_a,K_c} = 5_0,5–4_0,4\), \(\mathrm{HC}_3\)N \(J = 11–10, 12–11, \) and \(\mathrm{CH}_3\)CN \(J = 6_{K = 6}–5_{K = 5}\), and are the first interferometric images for the rotational lines in NGC 1068.

1. \(^{13}\)CN: The image was made using two fine structure lines \((j = 3/2–1/2\) and \(1/2–1/2\)) of the \(N = 1–0\) transition. Although the signal-to-noise ratio is low, \(^{13}\)CN may be distributed both in the east and west knots in the CND. It is not clear whether \(^{13}\)CN is distributed in the starburst ring, because the clumpy ring-like structure looks different from those of the CO isotopic species and \(\mathrm{CH}_3\)OH. Previously, the \(\mathrm{CN}N = 2–1\) image was reported by García-Burillo et al.
Fig. 1. Images of integrated intensity of $^{13}\text{CO}$ $J = 1-0$, $^{18}\text{O}$ $J = 1-0$, CS $J = 2-1$, and CH$_3$OH $J_K = 2K-1K$. The central radio continuum position [RA (J2000.0) = $2^h42^m40^s0912$ and Dec (J2000.0) = $-0^\circ00'47'.9449$; Gallimore et al. 2004] and the $^{13}\text{CO(0x0000FF) J = 3-2}$ intensity peak at the south-west position in the starburst ring [RA (J2000.0) = $2^h42^m40^s298$ and Dec (J2000.0) = $-0^\circ01'01'.638$; Nakajima et al. 2014] are indicated with white crosses. The beam is shown with an open white ellipse in the bottom-left corner in each image. The primary beam correction is not applied.

(2010), who used the IRAM Plateau de Bure interferometer. Their results show distributions both in the east and west knots in the CND; the intensity is stronger in the east knot than in the west knot. These facts support our results for $^{13}\text{CN}$ in the CND. Since their field of view is 21", the image does not cover the starburst ring.

2. SO: The image is concentrated in the CND.

3. HNCO: Although the signal-to-noise ratio is low, HNCO may be distributed both in the east and west knots in the CND, and is distributed in the starburst ring, though it is not clearly seen in the image. As shown later, the distribution of HNCO in the starburst ring is confirmed from the detection of its spectral line in the south-west point of the starburst ring.

4. HC$_3$N: The image is concentrated in the CND as seen from two rotational emission lines.

5. CH$_3$CN: The image is concentrated in the CND.

3.2 Spectra at the circumnuclear disk and the starburst ring (south-west)

Spectra were obtained from cleaned images at the following two positions: (1) the central radio continuum peak (AGN) in the CND [RA (J2000.0) = $2^h42^m40^s0912$ and Dec (J2000.0) = $-0^\circ00'47'.9449$; Gallimore et al. 2004], and (2) the $^{13}\text{CO J = 3-2}$ intensity peak at the south-west position in the starburst ring [RA (J2000.0) = $2^h42^m40^s298$ and Dec (J2000.0) = $-0^\circ01'01'.638$; Nakajima et al. 2014].

Before obtaining the spectra, the images in the two spectral windows in the USB were convolved with the beam of the spectral window in the lowest frequency in the LSB, and then attenuation due to the primary beam pattern of the ALMA 12-m antennas was corrected. The velocity resolution is $\sim 19.0$ km s$^{-1}$ at 100 GHz. The obtained spectra are shown in figure 3.

In the CND, the detected lines are broad, with a width of about 200 km s$^{-1}$ full width at half-maximum (FWHM). $^{18}\text{O}$ is not clearly detected, and $^{13}\text{CN}$ is marginally detected in the CND. On the other hand, the detected lines in the south-west position of the starburst ring are narrow, with a width of about 20–45 km s$^{-1}$ FWHM. Detections of SO$J_N = 3_2-2_1$, HC$_3$N$J = 11-10$, 12-11, and HNCO$J_{K_a,K_c} = 5_0,5-4_0,4$ clearly indicate the existence of such molecules there, which is not unambiguously determined by the
Fig. 2. Images of integrated intensity of SO \(J_N = 3-2\), \(^{13}\)CN \(N = 1-0\), HC\(_3\)N \(J = 11-10, 12-11\), HNCO \(J_K = 5\), and CH\(_3\)CN \(J_K = 6\) transitions. The central continuum position and the \(^{13}\)CO \(J = 3-2\) intensity peak at the south-west position in the starburst ring are indicated with white crosses (see the caption of figure 1). The beam is shown with an open white ellipse in the bottom-left corner in each image. The primary beam correction is not applied.

images in figure 2. The CH\(_3\)CN \(J_K = 6\) transition was not detected. The detected lines were Gaussian-fitted, and the line parameters obtained are summarized in table 2.

3.3 The flux at the circumnuclear disk and the south-west position in the starburst ring

As presented in figures 1 and 2, the distributions of molecules show wide diversity. In order to obtain quantitative information of the distributions, we extracted the flux for each molecule both in the CND and the south-west position in the starburst ring (SW). The derived flux ratio (CND/SW) was then used to determine a general trend.

The flux in the CND and SW was obtained within a circle of 10" diameter. These circles are centered, respectively, on the radio continuum peak (Gallimore et al. 2004) and the south-west position mentioned in subsection 3.2. The results are listed in table 3. The error for each flux is obtained from the rms noise of the image at emission-free regions, but the systematic deviation is not included.
The spectra are shown at the central continuum position and the $^{13}\text{CO} J=3–2$ intensity peak at the south-west position in the starburst ring (see the caption of figure 1). The primary beam correction is applied. Different colors of the spectra indicate different spectral windows (spw0, 1, 2, and 3). The frequency is shown as toponometric value, which is a default reference frame of ALMA. It is necessary to shift the frequency corresponding to $V_{LSR} = 1150 \text{ km s}^{-1}$ to obtain approximate rest frequency.

For images with low signal-to-noise ratios, it is difficult to obtain a reliable flux. In such a case, lower limits to the CND/SW flux ratio are listed in table 3 for molecules with a low signal-to-noise ratio in the south-west position. Such ratios are obtained based on the errors of the flux in the south-west position. For molecules with low signal-to-noise ratios in both the CND and the south-west position, ratios are not listed in this table. We also note that the accuracy of the $^{13}\text{CO}$ flux in the CND may be limited by the dynamic range of the data (A. Taniguchi et al., in preparation), because the emission from the CND is surrounded by much stronger sources of emission along the starburst ring.

The value of the flux ratio ranges widely from $\sim 0.1$ to more than 3. By comparing the ratio and the image, we can approximately establish the correspondence between

| Table 2. Line parameters of the detected lines. |
|-----------------------------------------------|
| Frequency [MHz] | Molecular Transition | Frequency measured in laboratory (Lovas 1992) | $^{13}\text{CO}$ | Ionized line | Frequency measured in laboratory (Lovas 1992) | $^{13}\text{CO}$ | Ionized line |
|-----------------|----------------------|---------------------------------------------|-----------------|-------------|---------------------------------------------|-----------------|-------------|
| 98741.42        | CH$_3$OH             | $^2S_1-^2S_3$                                | 97980,964       | CS          | $^2S_1-^2S_3$                                | 97929,879       | CS          |
| 97980,964       | CS                   | $^2S_1-^2S_3$                                | 97929,879       | CS          | $^2S_1-^2S_3$                                | 97929,879       | CS          |
| 100076,389      | HC$_3$N              | $^2S_1-^2S_3$                                | 100076,389      | HC$_3$N     | $^2S_1-^2S_3$                                | 100076,389      | HC$_3$N     |
| 100978.201      | CH$_3$OH             | $^2S_1-^2S_3$                                | 100978.201      | CH$_3$OH    | $^2S_1-^2S_3$                                | 100978.201      | CH$_3$OH    |
| 101005.735      | CH$_3$OH             | $^2S_1-^2S_3$                                | 101005.735      | CH$_3$OH    | $^2S_1-^2S_3$                                | 101005.735      | CH$_3$OH    |
| 101053.333      | CH$_3$OH             | $^2S_1-^2S_3$                                | 101053.333      | CH$_3$OH    | $^2S_1-^2S_3$                                | 101053.333      | CH$_3$OH    |
| 101053.333      | CH$_3$OH             | $^2S_1-^2S_3$                                | 101053.333      | CH$_3$OH    | $^2S_1-^2S_3$                                | 101053.333      | CH$_3$OH    |
| 101053.333      | CH$_3$OH             | $^2S_1-^2S_3$                                | 101053.333      | CH$_3$OH    | $^2S_1-^2S_3$                                | 101053.333      | CH$_3$OH    |
| 101053.333      | CH$_3$OH             | $^2S_1-^2S_3$                                | 101053.333      | CH$_3$OH    | $^2S_1-^2S_3$                                | 101053.333      | CH$_3$OH    |
| 101053.333      | CH$_3$OH             | $^2S_1-^2S_3$                                | 101053.333      | CH$_3$OH    | $^2S_1-^2S_3$                                | 101053.333      | CH$_3$OH    |
| 101053.333      | CH$_3$OH             | $^2S_1-^2S_3$                                | 101053.333      | CH$_3$OH    | $^2S_1-^2S_3$                                | 101053.333      | CH$_3$OH    |
| 101053.333      | CH$_3$OH             | $^2S_1-^2S_3$                                | 101053.333      | CH$_3$OH    | $^2S_1-^2S_3$                                | 101053.333      | CH$_3$OH    |
| 101053.333      | CH$_3$OH             | $^2S_1-^2S_3$                                | 101053.333      | CH$_3$OH    | $^2S_1-^2S_3$                                | 101053.333      | CH$_3$OH    |
| 101053.333      | CH$_3$OH             | $^2S_1-^2S_3$                                | 101053.333      | CH$_3$OH    | $^2S_1-^2S_3$                                | 101053.333      | CH$_3$OH    |
Table 3. Flux of each molecule in the circumnuclear disk (CND) and in the south-west position in the starburst ring.*

| Molecule | Flux in the CND$^1$ (Jy km s$^{-1}$) | Flux in the SW position$^1$ (Jy km s$^{-1}$) | Ratio (CND/SW)$^2$ | Main distribution |
|----------|-------------------------------------|----------------------------------------|--------------------|------------------|
| CH$_3$OH | 1.05 ± 0.59                         | 1.27 ± 0.70                            | 0.82 ± 0.65        | CND & starburst ring |
| CS       | 10.4 ± 0.9                          | 5.35 ± 1.11                            | 1.94 ± 0.44        | CND & starburst ring |
| SO       | 1.78 ± 0.59                         | 0.32 ± 0.71$^3$                        | > 2.5              | CND |
| HC$_3$N/J = 11–10 | 3.67 ± 0.85               | 0.38 ± 1.03$^3$                        | > 3.6              | CND |
| HC$_3$N/J = 12–11 | 3.34 ± 1.36               | 0.82 ± 1.69$^3$                        | > 2.0              | CND |
| $^{13}$CN | 1.55 ± 0.92                         | 0.01 ± 1.14$^3$                        | —                  | (at least) CND |
| C$^{18}$O | 0.34 ± 1.32$^3$                     | 8.41 ± 1.64                           | 0.04 ± 0.16        | starburst ring |
| HNCO     | 1.27 ± 0.80                         | 0.59 ± 1.00$^3$                       | —                  | (at least) CND |
| $^{13}$CO| 3.07 ± 1.62                         | 26.4 ± 2.0                            | 0.12 ± 0.06        | starburst ring |
| CH$_3$CN | 1.61 ± 1.08                         | 0.33 ± 1.35$^3$                        | > 1.2              | CND |

*For details, see subsection 3.3.
$^1$Flux within the circle with the diameter of 10".
$^2$For molecules with low signal-to-noise ratio in the south-west position, ratios of lower limit are listed. Such ratios are obtained based on the errors of the flux in the south-west position. In addition, for molecules with low signal-to-noise ratio in both the CND and the south-west position, ratios are not listed.
$^3$In the case of low signal-to-noise ratio, it is difficult to obtain a reliable flux.

The flux ratio (CND/south-west position in the starburst ring) is presented for each molecule. In the case of HC$_3$N two transitions are presented: $J = 11$–10 (left) and $J = 12$–11 (right). For details, see subsection 3.3.

3.4 Comparison of flux with single-dish telescopes

We compared the flux obtained from ALMA with those from single-dish telescopes (NRO 45 m and IRAM 30 m) to estimate the recovery of the flux with the interferometer. First, the flux of $^{13}$CO was compared. The image obtained with ALMA, with the primary beam corrected, was convolved with the 45-m beam of 16", and the flux obtained was converted to a brightness temperature of $\sim 8.1$ K km s$^{-1}$. The corresponding value obtained with the 45-m telescope is $\sim 8.9$ K km s$^{-1}$, which was observed in the recent line survey project (Nakajima et al. 2014; S. Takano et al. in preparation). Therefore, the recovered flux is about 92%. The same comparison was carried out by convolving the ALMA data with the 30-m beam of 22", and the flux obtained was once again converted to brightness temperature, this time $\sim 10.1$ K km s$^{-1}$. The corresponding value obtained with the 30-m telescope is $\sim 12.8$ K km s$^{-1}$ (Aladro et al. 2013), so that the recovered flux is about 79%. The 30-m telescope can observe widely distributed gas more efficiently than the 45-m telescope due to the larger beam size, but ALMA is less sensitive to such gas. The difference in the values of the recovery may include such an effect.

Second, the flux of CS, which is more compactly distributed than $^{13}$CO, was compared. The image obtained with ALMA, with primary beam corrected, was convolved with the 45-m beam of 17", and the flux obtained was converted to a brightness temperature of $\sim 5.9$ K km s$^{-1}$. The corresponding value obtained with the 45-m telescope is $\sim 8.0$ K km s$^{-1}$ (Nakajima et al. 2014; S. Takano et al. in preparation). Therefore, the recovered flux is about 74%. The comparison with the CS data of the 30-m telescope was not done, because the line is blended with a line from the other sideband (Aladro et al. 2013). These results of $^{13}$CO and CS indicate that ALMA observes most of the flux in the central region of NGC 1068.
4 Discussion

4.1 Classification of molecular distributions

As presented in figures 1 and 2, the molecules exhibit a wide variety of distributions, which are reflections of abundance and excitation. Such distributions contain important information to study the effects on molecules caused by AGN activity and starburst conditions. As already mentioned in the previous sections, we can classify molecular distributions into three broad categories: (1) molecules concentrated in the CND, (2) molecules distributed both in the CND and the starburst ring, and (3) molecules distributed mainly in the starburst ring. Based on addition in the spectra shown in figure 3 and on the flux ratio (CND/SW) in table 3, each molecule was further classified as listed in table 4, where the above categories (1) and (2) were subdivided as follows: (i) molecules distributed in two knots in the CND, and (ii) molecules distributed in the center of the CND.

Higher spatial resolution and a better signal-to-noise ratio are desirable for this more precise classification, but indications of such differences can be seen in the present images. Our beam size is ∼4′′ × 2′′ with north–south elongation, as compared with the separation between the two knots, which is about 3″. The present configuration, in which the direction of the two knots (east–west) is perpendicular to the elongation (north–south) of the beam contributes to the resolution of the structure.

In table 4, a refined classification of HCN (J = 1–0), HCO+ (J = 1–0), and SiO (J = 2–1) is included based on their images in the literature (e.g., Jackson et al. 1993; Kohno et al. 2008; García-Burillo et al. 2010). Distributions of 13CO, C18O, CN, and CS obtained from our ALMA band 7 data (Nakajima et al. 2014) are also included.

4.2 Implications for molecular formation and destruction mechanisms

The molecular distributions are reflections of both physical and chemical properties. Differences in temperature between the CND and the starburst ring have already been reported in the literature. According to spatially unresolved ammonia observations by Ao et al. (2011) with the Green Bank Telescope, there are two kinetic temperature components of T_K = 80 K and T_K > 140 K. One would assume that the higher temperature component is associated with the CND, since we know that a high-luminosity AGN exists though there is no direct evidence. But the spatially resolved CO (J = 3–2)/CO (J = 1–0) intensity ratio observed with the Submillimeter Array and OVRO by Tsai et al. (2012) suggests that the CND lies at higher excitation. Krips et al. (2011) obtained T_K ≥ 200 K and a density of ∼ 10^4 cm^{-3} based on the line ratios of 12CO and 13CO in the CND.

In addition to the differences in temperature, differences in density between the CND and the starburst ring can be of importance. We have estimated the critical densities for the transitions reported in this study using a variety of inelastic collisional rates involving H2 or He and Einstein A coefficients collected in the databases BASECOL (Besançon Molecular Collisional Database) (Dubernet et al. 2013) and LAMDA (Leiden Atomic and Molecular Database) (Schöier

Table 4. Classification of molecular distributions in the circumnuclear disk (CND) and the starburst ring.

| Category and molecule | |
|-----------------------|-----------------|
| 1. Molecules concentrated in the CND | |
| (i) Distributed both in the east and west knots | 13CN (N = 1–0)*, HNCO (J_{K_a,K_c} = 5_0,5,4_0,4)\textsuperscript{+}, CN (N = 3–2)\textsuperscript{+}, CS (J = 7–6)\textsuperscript{+} |
| (ii) Distributed in the center | SO (J_N = 3_2–2_1)\textsuperscript{+}, SiO (J = 2–1)\textsuperscript{+}, HC_3N (J = 11–10, 12–11)\textsuperscript{+}, CH_3CN (J_K = 6_0–5_0) |
| 2. Molecules distributed both in the CND and the starburst ring | |
| (i) Distributed both in the east and west knots in the CND | CH_3OH (J_K = 2_0–1_0), 13CO (J = 3–2)\textsuperscript{+} |
| (ii) Distributed in the center in the CND | CS (J = 2–1), HCN (J = 1–0)\textsuperscript{+}, HCO+ (J = 1–0)\textsuperscript{+} |
| 3. Molecules distributed mainly in the starburst ring | 13CO (J = 1–0), C18O (J = 1–0, 3–2)\textsuperscript{+} |

*Note that the signal-to-noise ratio is not high.
1Relatively small portion of the flux is detected in the south-western part of the starburst ring (see figure 3).
2Based on García-Burillo et al. (2010).
3Based on Jackson et al. (1993), Tacconi et al. (1994), and Kohno et al. (2008).
4See Nakajima et al. (2014).
et al. 2005). Our values divide into three ranges: low, moderate, and high. The low critical density occurs for CO ($J = 1–0$) isotopomers, for which we obtain a value of $\sim 2 \times 10^3$ cm$^{-3}$, while the moderate value pertains to the methanol transitions, for which we estimate a critical density of $4 \times 10^4$ cm$^{-3}$, slightly lower than the value of $\sim 6 \times 10^4$ estimated by Goldsmith, Langer, and Velusamy (1999). The remainder of the transitions possess high critical densities of $4 \times 10^5$–$2 \times 10^6$ cm$^{-3}$. Based solely on this analysis, and the assumption that the average density is higher in the CND than in the starburst ring, we can qualitatively reproduce the distinctions in flux ratio shown in table 3. Specifically, the high critical density transitions involving SO, HC$_3$N, and CH$_3$CN all show a CND/SW flux ratio significantly greater than unity, while CS, with the lowest high critical density, shows a low CND/SW flux ratio above unity. The methanol transitions, with a moderate critical density, show a flux ratio of slightly below unity. Thus there is evidence that densities above $10^5$ cm$^{-3}$ likely exist in large portions of the CND.

CO is a special case, since the low critical density for the $J = 1–0$ transition does not mean necessarily that the transition should be detected only weakly if at all in the CND. Nevertheless, our $^{13}$CO ($J = 1–0$) and C$^{18}$O ($J = 1–0$) distributions lie predominantly in the starburst ring. These distributions can be caused by a lower optical depth of the CO $J = 1–0$ transition in the CND than that in the starburst ring, as mentioned in subsection 3.1. The lower optical depth of the $J = 1–0$ transition in the CND is due to a low column density of CO and to a high excitation of CO (Nakajima et al. 2014; A. Taniguchi et al. in preparation). Such an excitation effect in the high-temperature and high-density environment of the CND is discussed below. In the CND the fraction of CO in the $J = 1$ level can be compared with that in the $J = 3$ level, which is the upper state for the $J = 3–2$ transition, strongly detected in the CND. For example, the ratios of the fractions of the $J = 3$ level to the $J = 1$ level of $^{13}$CO are calculated under the assumption of local thermodynamic equilibrium (LTE) to be 0.17, 0.62, 0.97, 1.20, and 1.37 at $T_{\text{rot}}$ of 10, 20, 30, 40, and 50 K, respectively. At temperatures greater than $\sim 35$ K, the ratio is greater than unity although this ratio does not reach 2 until a rotational temperature of $\sim 180$ K. As shown here, the ratio drastically changes at $T_{\text{rot}} \sim 10$–30 K, which is the range of the rotational temperature in the CND obtained from the analysis under LTE conditions (Nakajima et al. 2014). Thus, even under LTE conditions, it is possible that the difference in abundance between these two rotational levels plays a significant role.

On the other hand, CS ($J = 2–1$), with a critical density of $4 \times 10^5$ cm$^{-3}$ and CH$_3$OH ($J_K = 2_K–1_K$) with our estimate of $4 \times 10^4$ cm$^{-3}$ and a previous estimate of $\sim 6 \times 10^4$ cm$^{-3}$ (Goldsmith et al. 1999) are molecules with roughly similar critical density. Yet, these molecules do possess somewhat different distributions although they are found in both the CND and the starburst sources. In this case, these distributions may well reflect chemical differences. As explained above, the effect of a difference in chemistry between the CND and the starburst ring can be seen, if it exists, among molecules with similar excitation conditions. It is well known that CS is formed by gas-phase chemistry while methanol is formed by the hydrogenation of CO on dust surfaces and then desorbed into the gas, particularly at higher temperatures.

Taking into account such situations, we discuss the implications of specific molecular distributions below using a knowledge of the relevant chemical reactions and the results of chemical simulations. Further discussion will be undertaken after we obtain quantitative information such as the abundances in Nakajima et al. (2014) and A. Taniguchi et al. (in preparation). Here we mainly use the results of recent simulations by Harada, Herbst, and Wakelam (2010), Harada, Thompson, and Herbst (2013) and Aladro et al. (2013). Harada, Herbst, and Wakelam (2010) reported a gas-phase time-dependent reaction model including reactions with significant activation energies for high-temperature chemistry. Thus, this model can be used for high-temperature sources up to $\sim 800$ K. Harada, Thompson, and Herbst (2013) applied the results of Harada, Herbst, and Wakelam (2010) to the axisymmetric accretion disk around AGNs such as that in NGC 1068. The effects of X-rays and cosmic rays are included. Aladro et al. (2013) reported a time-dependent reaction model including gas-phase and grain surface reactions. The effects of UV photons and cosmic rays are included. A high cosmic ray ionization rate was used to simulate the environment in an X-ray dissociation region (XDR).

The intrinsic X-ray luminosity of NGC 1068 is estimated to be $1 \times 10^{43}$–$10^{44}$ erg s$^{-1}$ in the 2–10 keV range (Iwasawa et al. 1997; Colbert et al. 2002). Harada, Thompson, and Herbst (2013) show the effect of X-rays in different density structures of the CND using $L_X = 6 \times 10^{33}$ erg s$^{-1}$. According to their model, this high value of X-ray luminosity is able to create an XDR of greater than 100 pc in extent, as shown in the enhancement of species such as CN, when those regions are not obscured by large columns. When the obscuring column densities are high, relatively complex molecules such as HC$_3$N, which are prone to X-ray dissociation, can exist. In the Harada, Thompson, and Herbst (2013) figures of cross sections of the CND, such abundance structures can be clearly seen. Therefore, X-rays most probably affect the chemistry in the CND. In addition, the effect of X-rays on molecular abundances is discussed in García-Burillo et al. (2010). These authors
found correlations between the X-ray flux and the intensity ratio SiO ($J = 2–1)/CO (J = 1–0)$, and also between the X-ray flux and the intensity ratio CN ($N = 2–1)/CO (J = 1–0)$.

4.2.1 HC$_3$N

Because HC$_3$N is concentrated in the CND, its behavior cannot be explained if we consider the entire CND as an XDR, since HC$_3$N is easily dissociated by cosmic rays and UV photons (Aladro et al. 2013; Harada et al. 2013). On the other hand, the abundance of HC$_3$N increases at hot core regions and high-temperature (non-dissociative shocked) regions (Caselli et al. 1993; Harada et al. 2010). The model by Harada, Thompson, and Herbst (2013) shows that there is a high-temperature midplane where X-rays cannot penetrate into the CND in addition to a different layer that can be characterized as an XDR. Complex molecules are predicted to be abundant in the high-temperature zone. Our observations of HC$_3$N confirm that there is a large amount of gas which is sheltered from X-rays, and the local column densities of the CND should be very high. This fact yields information on the structure of the CND, which is quite interesting and relevant to an understanding of the physical and chemical environment in the central region. Further ALMA observations with higher angular resolution will reveal the structure.

4.2.2 CH$_3$OH

Methanol has a significant concentration in the CND as mentioned before. Just like HC$_3$N, methanol is easily dissociated by cosmic rays and UV photons (Aladro et al. 2013). Thus, the concentration of methanol in the CND also requires shielding. On the other hand, the inconsistent distribution of methanol in the starburst ring is very striking. The formation of methanol on icy dust grains is well known and it is not surprising that methanol should be abundant in active star-forming regions in the starburst ring.

To look at the matter further, we studied the relation of methanol intensity to the SFR (Tsai et al. 2012) in those regions with relatively strong methanol emission. We found the averaged SFR in regions with relatively strong methanol emission (roughly at regions R6, R9, R16, and R20–21 in Tsai et al. 2012) to be 1.40 ± 0.54 $M_\odot$ yr$^{-1}$ kpc$^{-2}$, whereas the average of all regions is 1.26 ± 0.46 $M_\odot$ yr$^{-1}$ kpc$^{-2}$. The averaged value of regions with relatively strong methanol emission is only slightly larger than that of all the regions. Moreover, the values at regions with relatively strong methanol emission have a large scatter from 0.97 to 2.26 $M_\odot$ yr$^{-1}$ kpc$^{-2}$ (Tsai et al. 2012) as indicated in the large standard deviation. Thus, we could not find a strong correlation between methanol intensity and the SFR. This result may be related to our spatial resolution and its coupling to the sizes of the regions above, or this may be due to the formation and destruction mechanisms in the environment of the starburst ring. A more detailed analysis will be published separately (T. Tosaki et al. in preparation).

The inconsistent distribution of CH$_3$OH in the starburst ring when compared with $^{13}$CO and/or C$^{18}$O, discussed here, was also reported in IC 342 (Meier & Turner 2005) and Maffei 2 (Meier & Turner 2012). In addition, CH$_3$OH is relatively weak in M 82 (e.g., Aladro et al. 2011), which is in a late stage of starburst activity. These presumably related results should be very helpful in interpreting the inconsistency in the starburst ring in NGC 1068, suggesting that methanol needs specific favorable conditions to form on grains and to subsequently sublime into the gas phase.

4.2.3 SO, HNCO, and CH$_3$CN

Because they are concentrated in the CND, the distributions of these molecules clearly indicate that the CND is a good environment to maintain their abundances. SO and CH$_3$CN are easily dissociated by UV photons, but the abundance of SO is enhanced by cosmic rays (Aladro et al. 2013). Thus, the XDR environment seems to be a favorable place for SO, but the concentration of CH$_3$CN also suggests shielded gas in the CND.

Similar to other molecules, HNCO can also be dissociated by UV photons, and it needs to be shielded. Although there is a gas-phase production route for this molecule, its abundance is known to increase when HNCO on dust surfaces sublimes (Quan et al. 2010).

The above mentioned molecules except CH$_3$CN (SO, HNCO, HC$_3$N, and CH$_3$OH) are weakly detected in the south-west starburst ring. These facts do not contradict the detections of these molecules in other starburst galaxies such as NGC 253 and M 82 (e.g., Martin et al. 2006; Aladro et al. 2011). However, the emission lines of SO, HC$_3$N, and CH$_3$CN in the CND are much stronger than those in the starburst ring. A possible reason for this is that the CND is likely to have a much higher density and temperature than the starburst ring. Besides exceeding the higher critical densities needed for these transitions, higher densities can allow more complex molecules to form without being destroyed by X-rays.

4.2.4 Two kinds of distributions in the CND

The molecules in the CND show two kinds of distributions as mentioned previously in subsection 4.1. Here we briefly discuss possible reasons for such a difference. Let us start with the case of SiO, which is distributed in the center, as
observed by García-Burillo et al. (2010), who also reported an enhanced SiO abundance and discussed its likely shock origin. Probably SiO is produced through the sputtering of Si-bearing material in grains (Caselli et al. 1997; Field et al. 1997; Schilke et al. 1997), and as a result SiO traces strong shocks in the central region. On the other hand, HNCO and CH$_3$OH are tracing relatively weak shocks, which result in the sublimation of HNCO and CH$_3$OH from the icy mantles of dust grains (e.g., Bachiller et al. 1995; Rodriguez-Fernández et al. 2010). Therefore, it seems that molecules produced in more energetic regions tend to exist closer to the center, while those produced in less energetic regions exhibit a bipolar pattern in the knots.

Krips et al. (2011) reported detailed distributions of the molecules $^{12}$CO, $^{13}$CO, C$^{18}$O, HCN, and HCO$^+$ in the CND. Since our beam sizes are larger than those of Krips et al. (2011), the comparison is not straightforward. However, the distribution of CH$_3$OH, which shows the image with the highest signal-to-noise ratio among the molecules distributed in both knots in our data, is similar to those of $^{12}$CO $J = 1–0$ and 3–2.

As shown in this study, the sensitive ALMA observations are very powerful probes of the distributions of molecules in gas-rich nearby galaxies such as NGC 1068 even in the early operation phase of ALMA. Other results and analysis of our ALMA data will be reported in our subsequent papers. Further observations of many other molecules will bring us additional valuable information to understand chemical processes in such environments.

5 Summary

We have observed the Seyfert 2 galaxy NGC 1068 in its central 1′ at the 100-GHz frequency region during the ALMA early science program; our observations included both the CND and the surrounding starburst ring with an angular resolution of $\sim 4″ \times 2″$ (290 pc $\times$ 140 pc).

1. We observed the rotational transitions $^{13}$CO $J = 1–0$, C$^{18}$O $J = 1–0$, $^{13}$CN N $J = 1–0$, CS $J = 2–1$, SO $J$N = 3–2, HNCO $J_{K,K}$ = $5_{0,5}$–$4_{0,4}$, H$_2$CN $J$ = 11–10, 12–11, CH$_3$OH $J$K = 2–1$K$, and CH$_3$CN $J$K = 6–5$K$. The molecular transitions show a wide variety of spatial distributions, which can be classified into three main categories: those molecular transitions concentrated in the CND, those distributed both in the CND and the starburst ring, and those mainly in the starburst ring. The distributions concentrated in the CND include $^{13}$CN, SO, HNCO, H$_2$CN, and CH$_3$CN; those distributed in the CND and starburst ring include CS and CH$_3$OH, while those mainly in the starburst ring include $^{13}$CO and C$^{18}$O. The first two categories were further subdivided into distributions in the two knots or in the center of the CND.

2. The molecular distributions are reflections of both physical and chemical properties. The transitions detected in the CND and not in the starburst region show high critical densities, indicating that the CND does possess a large fraction of gaseous regions with densities in excess of $10^5$ cm$^{-3}$, while the starburst regions likely do not. The $^{13}$CO ($J = 1–0$) and C$^{18}$O ($J = 1–0$) distributions lie predominantly in the starburst ring. The weak intensity of these lines in the CND can be due to the excitation effect in the high-temperature and high-density environment. On the other hand, CS ($J = 2–1$) and CH$_3$OH ($J = 2–1$) are one example of molecules with roughly similar critical densities, but with different distributions from each other. In this case, these distributions mainly reflect chemical differences; CS is made efficiently in the gas, while CH$_3$OH is made only on dust surfaces.

3. Molecules concentrated in the CND are easily dissociated by cosmic rays, X-rays, and/or UV photons. These facts indicate that there is a large amount of gas in the CND that is shielded especially from X-rays. This information constrains the structure of the CND. This point of view is consistent with the model calculations by Harada, Thompson, and Herbst (2013), who studied the chemistry occurring in the CND using a number of disk physical models. In their models, both XDR portions without much shielding and more shielded regions coexist. The intense emission of relatively large molecules, such as H$_2$CN and CH$_3$CN, in the CND compared with the starburst ring can be due to the relatively dense and hot gas in the shielded region in the CND.

4. The distribution of methanol in the starburst ring shows an inconsistent relative intensity with respect to those of $^{13}$CO, C$^{18}$O, and CS. In addition, the intensity of methanol does not seem to correlate with the star-formation efficiency, although methanol is thought to be formed on grain surfaces and sublimed into the gas-phase by external heating.

Note added in proof (2014 July 27):

After the acceptance of this paper, we noticed a preprint by García-Burillo et al. (2014, A&A, in press, arXiv:1405.7706), who mapped the CO ($J = 3–2$), CO ($J = 6–5$), HCN ($J = 4–3$), HCO$^+$ ($J = 4–3$), and CS ($J = 7–6$) transitions toward NGC 1068 with ALMA. The maps of CO ($J = 3–2$), HCN ($J = 4–3$), HCO$^+$ ($J = 4–3$), and CS ($J = 7–6$) covered both the...
CND and the starburst ring, and as a result CO ($J = 3 - 2$), HCN ($J = 4 - 3$), and HCO$^+$ ($J = 4 - 3$) were detected in both sources. Their high-resolution maps suggested that an outflow from the AGN is strongly affecting their molecular observations, and that this outflow may also be affecting the features seen in our observations.

Acknowledgments

This paper makes use of the ALMA data ADS/JAO.ALMA#2011.0.00061.S. ALMA is a partnership of ESO (representing its member states), NSF (USA) and NINS (Japan), together with NRC (Canada) and NSC and ASIAA (Taiwan), in cooperation with the Republic of Chile. The Joint ALMA Observatory is operated by ESO, AUI/NRAO and NAOJ. We thank the support of the East Asian ALMA Regional Center, in particular, A. Kawamura, for the support. ST thanks Y. Shimajiri, M. Oya, and S. Takahashi for the support of the analysis with CASA. EH wishes to acknowledge the support of the National Science Foundation for his astrochemistry program. He also acknowledges support from the NASA Exobiology and Evolutionary Biology program through a subcontract from Rensselaer Polytechnic Institute.

References

Aladro, R., Martin, S., Martin-Pintado, J., Mauersberger, R., Henkel, C., Ocaña Flaque, B., & Amo-Baladrón, M. A. 2011, A&A, 538, A84
Aladro, R., et al. 2013, A&A, 549, A39
Ao, Y., Henkel, C., Braatz, J. A., Weiß, A., Menten, K. M., & Mühle, S. 2011, A&A, 529, A154
Baan, W. A., Henkel, C., Loenen, A. F., Baudry, A., & Wiklind, T. 2008, A&A, 477, 747
Bachiller, R., Liechti, S., Walmsley, C. M., & Colomer, F. 1995, A&A, 295, L51
Bland-Hawthorn, J., Gallimore, J. F., Tacconi, L. J., Brinks, E., Baum, S. A., Antonucci, R. R. J., & Cecil, G. N. 1997, Ap&SS, 248, 9
Bradford, C. M., et al. 2004, SPIE Conf., 5498, 257
Carter, M., et al. 2012, A&A, 538, A89
Caselli, P., Harquist, T. W., & Hawkes, O. 1997, A&A, 322, 296
Caselli, P., Hasegawa, T. I., & Herbst, E. 1997, ApJ, 498, 548
Cid Fernandes, R., Heckman, T. M., Schuller, F., Gómez, J. L., Brinks, E., & Genzel, R. 2005, ApJ, 626, 731
Colbert, E. J. M., Weaver, K. A., Krolik, J. H., Mulchaey, J. S., & Naylor, B. J. 2010, ApJ, 722, 2101
Costagliola, F., et al. 2011, A&A, 528, A30
Davies, R., Mark, D., & Sternberg, A. 2012, A&A, 537, A133
Davies, R. I., Muller Sánchez, F., Genzel, R., Tacconi, L. J., Hicks, E. K. S., Friedrich, S., & Sternberg, A. 2007, ApJ, 671, 1388
Dubernet, M.-L., et al. 2013, A&A, 553, A50
Erickson, N., Narayanan, G., Goeller, R., & Grosslein, R. 2007, in ASP Conf. Ser., 375, From Z-Machines to ALMA: (Sub)Millimeter Spectroscopy of Galaxies, ed. A. J. Baker et al. (San Francisco: ASP), 71
Field, D., May, P. W., Pineau des Forets, G., & Flower, D. R. 1997, MNRAS, 283, 839
Gallimore, J. F., Baum, S. A., & O'Dea, C. P. 2004, ApJ, 613, 794
García-Burillo, S., et al. 2010, A&A, 519, A2
Goldsmith, P. F., Langer, W. D., & Velusamy, T. 1999, ApJ, 519, L173
Griffin, M. J., et al. 2010, A&A, 518, L3
Harada, N., Herbst, E., & Wakeham, V. 2010, ApJ, 721, 1570
Harada, N., Thompson, T. A., & Herbst, E. 2013, ApJ, 765, 108
Helfer, T. T., & Blitz, L. 1995, ApJ, 450, 90
Imanishi, M., Terada, H., Sugiyama, K., Motohara, K., Goto, M., & Maihara, T. 1997, PASJ, 49, 69
Imanishi, M., & Wada, K. 2004, ApJ, 617, 214
Iono, D., et al. 2012, PASJ, 64, L2
Iwasawa, K., Fabian, A. C., & Matt, G. 1997, MNRS, 289, 443
Izumi, T., et al. 2013, PASJ, 65, 100
Jackson, J. M., Paglione, T. A. D., Ishizuki, S., & Nguyen-Q-Rieu, 1993, ApJ, 418, L13
Kamenetzky, J., et al. 2011, ApJ, 731, 83
Kohno, K., Ishizuki, S., Matsushita, S., Vila-Vilaró, B., & Kawabe, R. 2003, PASJ, 55, L1
Kohno, K., Kawabe, R., Tosaki, T., & Okumura, S. K. 1996, ApJ, 461, L29
Kohno, K., Nakanishi, K., Tosaki, T., Muraoaka, K., Miura, R., Ezawa, H., & Kawabe, R. 2008, Ap&SS, 313, 279
Krips, M. 2012, J. Phys. Conf. Ser., 372, 012038
Krips, M., et al. 2007, A&A, 468, L63
Krips, M., et al. 2011, ApJ, 736, 37
Krips, M., Neri, R., García-Burillo, S., Martin, S., Combes, F., Graciá-Carpio, J., & Eckart, A. 2008, ApJ, 677, 262
Lovas, F. J. 1992, J. Phys. Chem. Ref. Data, 21, 181
Martin, S., et al. 2011, A&A, 527, A36
Martin, S., Mauersberger, R., Martin-Pintado, J., Henkel, C., & García-Burillo, S. 2006, ApJS, 164, 450
Meier, D. S., & Turner, J. L. 2005, ApJ, 618, 259
Meier, D. S., & Turner, J. L. 2012, ApJ, 755, 104
Meijerink, R., & Spaans, M. 2005, A&A, 436, 397
Meijerink, R., Spaans, M., & Israel, F. P. 2003, A&A, 461, 793
Muxlow, T. W. B., Pedlar, A., Holloway, A. J., Gallimore, J. F., & Antonucci, R. R. J. 1996, MNRS, 278, 854
Nakajima, T., et al. 2013, PASP, 125, 252
Nakajima, T., et al. 2014, PASJ submitted
Nakajima, T., Takano, S., Kohno, K., Kawabe, R., & Inoue, H. 2011, ApJ, 728, L38
Naylor, B. J., et al. 2010, ApJ, 722, 668
Papadopoulos, P. P., Scoville, N. Z. 1996, ApJ, 465, 173
Quan, D., Herbst, E., Osamura, Y., & Roueff, E. 2010, ApJ, 725, 2101
Rangwala, N., et al. 2011, ApJ, 743, 94
Rodríguez-Fernández, N. J., Tafalla, M., Gueth, F., & Bachiller, R. 2010, A&A, 516, A98
Sani, E., et al. 2012, MNRS, 424, 1963
Schilke, P., Walmsley, C. M., Pineau des Forets, G., & Flower, D. R. 1997, A&A, 321, 293
Schinnerer, E., Eckart, A., Tacconi, L. J., Genzel, R., & Downes, D. 2000, ApJ, 533, 850
Schneider, F. L., van der Tak, F. F. S., van Dishoeck, E. F., & Black, J. H. 2005, A&A, 432, 369
Snell, R. L., Narayanan, G., Yun, M. S., Heyer, M., Chung, A.,
Irvine, W. M., Erickson, N. R., & Liu, G. 2011, AJ, 141, 38
Spinoglio, L., et al. 2012, ApJ, 758, 108
Tacconi, L. J., Gallimore, J. F., Genzel, R., Schinnerer, E., &
Downes, D. 1997, Ap&SS, 248, 59
Tacconi, L. J., Genzel, R., Blietz, M., Cameron, M., Harris, A. I., &
Madden, S. 1994, ApJ, 426, L77
Telesco, C. M., & Decher, R. 1988, ApJ, 334, 573

Tsai, M., Hwang, C.-Y., Matsushita, S., Baker, A. J., & Espada, D.
2012, ApJ, 746, 129
Tully, R. B. 1988, Nearby galaxies catalog (Cambridge: Cambridge
University Press)
Usero, A., García-Burillo, S., Fuente, A., Martín-Pintado, J., &
Rodríguez-Fernández, N. J. 2004, A&A, 419, 897
van der Werf, P. P., et al. 2010, A&A, 518, L42
Watanabe, N., & Kouchi, A. 2002, ApJ, 571, L173