ALMA [C I] observations toward the central region of a Seyfert galaxy NGC 613

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Received 2017 November 21; Accepted 2018 February 1

Abstract

We report ALMA observations of [C I](3P_1 − 3P_0), 13CO, and C^{18}O(J = 1 − 0) toward the central region of a nearby Seyfert galaxy NGC 613. The very high resolutions of 0″.26 × 0″.23 (=22 × 20 pc) for [C I] and 0″.42 × 0″.35 (=36 × 30 pc) for 13CO, and C^{18}O resolve the circum-nuclear disk (CND) and star-forming ring. The distribution of [C I] in the ring resembles that of the CO emission, although [C I] is prominent in the CND. This can be caused by the low intensities of the CO isotopes due to the low optical depth under the high temperature in the CND.

We found that the intensity ratios of [C I] to 12CO(3–2) (R_{CI/CO}) and to 13CO(1–0) (R_{CI/13CO}) are high at several positions around the edge of the ring. The spectral profiles of CO lines mostly correspond each other in the spots of the ring and high R_{CI/CO}, but those of [C I] at spots of high R_{CI/CO} are different from CO. These results indicate that [C I] at the high R_{CI/CO} traces different gas from that traced by the CO lines. The [C I] kinematics along the minor axis of NGC 613 could be interpreted as a bubbly molecular outflow. The outflow rate of molecular gas is higher than star formation rate in the CND. The flow could be mainly boosted by the AGN through its radio jets.

Key words: galaxies: individual (NGC 613) — galaxies: ISM — galaxies: active — ISM: jets and outflows — radio lines: ISM

1 Introduction

Molecular hydrogen (H_2) is a major component of the interstellar medium in galaxies. While 12CO(J = 1–0) line has been used as a principal probe to trace molecular gas and to study dynamics and molecular gas distribution in galaxies, 12CO is not easy to estimate the gas mass due to the large optical depth. Recently, atomic carbon (C I) attracts attention as a good tracer of mass of the cold molecular gas especially in high redshift galaxies or metal-poor objects (e.g., Papadopoulos & Greve 2004, Papadopoulos et al. 2004).
It has been recognized that C I exists predominantly in the thin layer near the surface of molecular clouds exposed to UV radiation, which is called a photodissociation region (PDR) (Tielens & Hollenbach 1985, Hollenbach et al. 1991). However, large-scale C I (P3-2 P2), hereafter simply referred as [C I], mapping of the Orion A and B molecular clouds revealed that [C I] coexists with 12CO and 13CO(1–0) and their intensities correlate each other (Ikedo et al. 2002). Since the critical density of [C I] is similar to that of 12CO (n ≈ 10^3 cm⁻³), these findings indicate that the emission lines arise from the same volume and share similar excitation temperature.

The global extent of the [C I] emission is similar to that of dense molecular gas traced by C18O, whereas the intensities of [C I] and C18O anti-correlates to each other (e.g., Maezawa et al. 1999). Oka et al. (2005) showed distribution of the C I-to-12CO intensity ratio on the Galactic scale and suggested that the locations of the high intensity ratio correspond to the upstream of spiral arms. These results indicate that [C I] abundance is high in the early stage of chemical evolution (within a timescale for conversion from C I to CO; ~10⁸ yr) and [C I] traces young clouds which are just forming dense cores (Suzuki et al. 1992, Maezawa et al. 1999).

A couple of dozen observations toward nearby galaxy centers with single-dish telescopes whose linear resolution of several 100 pc have been found that the intensity ratio of [C I] to 13CO in most galaxy centers exceeds unity, being rare for the Galactic molecular clouds, and is likely related with the central activities (Israel 2005). The central outflow or shock may enhance [C I] compared with CO(1–0) (Krips et al. 2016), indicating a possibility of [C I] as an outflow or shock tracer. On the other hand, the distribution of [C I] is still unclear due to a few mapping observations with the limited spatial resolution (e.g., Gerin & Phillips 2000). For characterizing molecular clouds traced by C I, it is necessary to clarify the distributions of C I and CO lines relative to energetic activities, such as star formation and central outflow.

Molecular gas in barred galaxies can be transported toward the galactic center, because the galactic bar can effectively drain the angular momentum of the gas (Binney & Tremaine 2008, and references therein). The gas gathers at the region of nearly circular orbits (x2 orbits) and forms a nuclear ring which is the site of vigorous star formation (r ~ a few 100 pc; we refer to a star-forming ring). Star-forming rings are promising reservoirs of the gas that feeds to the accretion disks in active galactic nuclei (AGN) via the circum-nuclear disk (CND; r ~ 1 – 100 pc).

The nearby galaxy NGC 613 hosts a low-luminosity AGN and prominent radio jets from the center (e.g., Goulding & Alexander 2009, Hummel & Jorsater 1992). The central CND of NGC 613 (r <~ 90 pc) contains abundant molecular gas, while the star formation rate (SFR) in the CND is lower than that in its star-forming ring (250 <~ r <~ 340 pc), which is probably caused by the interaction between the jets and gas in the CND (Falcón-Barroso et al. 2014, Davies et al. 2017, Miyamoto et al. 2017). Comparisons between [C I] and CO lines in the energetic activities could provide clues to understanding what [C I] traces. This letter reports [C I] and CO observations with higher resolution enough to resolve the central region of the galaxy, i.e., CND and star-forming ring, for the first time as a galaxy.

2 Observations

NGC 613 was observed with the Atacama Large Millimeter/submillimeter Array (ALMA) using Bands 3 and 8 receivers. For Band 8, the Atacama compact array (ACA) and total power array (TP) were used in addition to the 12-m array. The synthesized beams at Bands 3 and 8 were 0′.42 × 0′.35 (θ = −29°) and 0′.26 × 0′.23 (θ = −71°), corresponding to 36 × 30 and 22 × 20 pc, respectively, at the distance of the galaxy (17.5 Mpc; Tully 1988). Single-point observations and three-point mosaic observations were conducted for Band 3 and Band 8, respectively. The maximum recoverable scale for Band 3 is ~22″. These setups allowed us to image the CND and star-forming ring of NGC 613. The phase reference center of (α2000.0, δ2000.0) = (1h34m18s.19, −29d56m06s.60) was adopted (Miyamoto et al. 2017). The correlators for Band 3 were configured to set three spectral windows in the upper sideband to measure 13CO(1–0) (νrest =110.201354 GHz) and C18O(1–0) (νrest =109.782176 GHz) in the 2SB dual-polarization mode. The correlators for Band 8 were configured to set one spectral window in the upper sideband to cover C I(P3-2 P2) (νrest =492.160651 GHz), in the dual-polarization mode. The flux density at the Band 3 was calibrated by J2357-5311 and J0334-4008, and at Band 8 by J0006-0623 and Uranus. The time variations of amplitude and phase were calibrated by J0106-2718 and J0145-2733 for Band 3 and by J0204-1701 and J0137-2430 for Band 8.

The data were processed using the Common Astronomy Software Application (CASA; McMullin et al. 2007). The velocity resolution of each line data obtained at different observing tracks with the 12 m array and ACA were separately rearranged to be 10 km s⁻¹. Each line data was then combined after subtracting continuum emission determined at the channels that are free from spectral line emission. To image the continuum emission, we used the flux density at the emission-free channels. The imaging was performed using the CLEAN-algorithm in CASA. CLEAN maps were obtained considering the Briggs weighting mode on the data with robustness of 0.5 for Band 3 and the natural weighting mode for Band 8. The resultant maps were 1500 × 1500 pixels with 0′.05 per pixel and 0′.02 per pixel for Band 3 and 8, respectively. For line emission of Band 8, TP data were calibrated through flagging and
Fig. 1. (a) Integrated intensity map of $^{12}\text{C}I(3 P_1 - 3 P_0)$. The contours are 5,10,20,30,40,50,60,70 and 80 $\sigma$ where $1 \sigma = 10$ K km s$^{-1}$. (b) The $^{12}\text{C}I$ velocity field map derived from intensity-weighted mean velocities. The velocity is in km s$^{-1}$ with respect to LSR and the radio definition. (c) Integrated intensity map of $^{13}\text{C}O(1 - 0)$. The contours are 5, 15, 30, 40, 50, and 100 $\sigma$ where $1 \sigma = 2$ K km s$^{-1}$. (d) Integrated intensity map of $^{18}\text{C}O(1 - 0)$. The contours are 5, 10, 15, 20, 35, 30, 35, 40, and 45 $\sigma$ where $1 \sigma = 2$ K km s$^{-1}$. A cross in each map is the peak position of the continuum emission, i.e., the galactic center, $(\alpha_{2000.0}, \delta_{2000.0}) = (1^h34^m18^s19, -29^\circ25'06'60)$. The filled ellipse in the bottom right corner of each map represents the beam size, $0''.26 \times 0''.23$ ($\theta = -71^\circ$) for $^{12}\text{C}I$ and $0''.42 \times 0''.35$ ($\theta = -29^\circ$) for $^{13}\text{C}O$ and $^{18}\text{C}O(1 - 0)$.

3 Results and Discussion

3.1 Distributions of $[\text{C}]I$ and CO lines

We found that the peak position of 100-GHz continuum corresponds to the phase center with the uncertainty of $\sim 0''.01$, while the peak position of 490-GHz continuum is offset from the phase center by $\sim 0''.07$, which is caused by large separation of 14$''$.2 between NGC 613 and the phase calibrator (J0204-1701). We, therefore, shifted the position in Band 8 data so that the continuum position coincides with the center.

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Fig. 2. (a) Map (color) of the integrated intensity ratio of $I_{13}$ to $I_{12}$, which is from Miyamoto et al. (2017), overlaid with $I_{12}$ contours of 5,10,15,20,30,50,100,150 and 180 $\sigma$ where $\sigma = 20$ km s$^{-1}$. (b) Same as (a) but contours of the 100-GHz flux (3.5,7,9,12 and 15 $\sigma$ where $\sigma = 20$ $\mu$Jy beam$^{-1}$). (c) Map (color) of the integrated intensity ratio of $I_{13}$ to $I_{12}$, overlaid with $I_{13}$ contours (same as figure 1(b)). (d) Map (color) of the integrated intensity ratio of $I_{13}$ to $I_{12}$, overlaid with $I_{13}$ contours (same as figure 1(c)).

Figure 2(a) and (c) show the integrated line ratios of [CI] to $^{12}$CO(3–2) ($\equiv R_{\text{CI/CO}}$) and to $^{13}$CO(1–0) ($\equiv R_{\text{CI/13CO}}$), where the $^{12}$CO intensity map is from Miyamoto et al. (2017) and the beam size of [CI] is convolved with those of the CO. For comparison, the distribution of 100-GHz continuum, whose flux density can be dominated by free-free thermal emission from H II regions followed by non-thermal emission, such as radio jets (e.g., Condon 1992, Salak et al. 2017), superposed on the ratio map of $R_{\text{CI/CO}}$ in figure 2(b). The $R_{\text{CI/CO}}$ is in a range of 0.1–0.3 in both the CND and star-forming ring and there are several high $R_{\text{CI/CO}}$ spots at the edge of the ring. The temperature ratio of [CI] to CO at the spots of the edge, $T_{\text{CI}}/T_{\text{CO}} \sim 0.6$, is enhanced more than double that in the ring, $\sim 0.1 - 0.3$ (see channel map in supplementary material). The high $R_{\text{CI/13CO}}$ likely locates around the bright spots in 100-GHz continuum, although not being always, e.g., south-west region. The $R_{\text{CI/13CO}}$ is strikingly very high in the CND due to the low intensity of $^{13}$CO, although being high at the edge of the ring as the case in $R_{\text{CI/CO}}$. The low intensity of $^{13}$CO relative to $^{12}$CO (and C I) in the CND can be due to the low optical depth, not by the extreme abundance of $^{13}$CO, which is caused by selective photo-dissociation, fractionation, or nucleosynthesis (e.g., Langer et al. 1984, van Dishoeck & Black 1988, and Casoli et al. 1992). The selective photo-dissociation and nucleosynthesis are inconsistent with the lower star formation activity in the CND than that in the ring (Falcón-Barroso et al. 2014). In addition, the lower intensity ratio of $^{13}$CO to $^{12}$CO in the CND than that in the ring [figure 2(d)] cannot be explained by the fractionation, since the high temperature in the CND (e.g., $T_k = 350 - 550$ K; Miyamoto et al. 2017) makes the formation of $^{13}$CO ineffective, by contrast with $^{18}$O which does not undergo the fractionation. We found that $R_{\text{CI/13CO}}$ of $\sim 10$ in the CND is consistent with the ratio of the optical depths of $\tau_{\text{CI}} = 0.6 \pm 0.3 \tau_{\text{13CO}} = 0.06 \pm 0.01$. In addition, it is expected that the low optical depth and high temperature in the CND cause the ratio of the fractions of the upper state level of $^{12}$CO (and $^{18}$O) to the $J = 1$ level. In NGC 1068, a case that the intensities of CO isotopic species of the $J = 1 - 0$ transition in the CND are lower than those in the ring and those of the
higher transition $J = 3 - 2$ in the CND was reported (Takano et al. 2014, Nakajima et al. 2015)

Figure 3 shows the spectra of [C I], $^{12}$CO(3–2), $^{13}$CO(1–0) and C$^{18}$O(1–0) at representative positions on the CND and ring. Spots 1, 3, 5, and 7 are peaks on the ring traced by CO(3-2) and $^{13}$CO(1-0) [see figure 2(a) and (c)], whereas spots 2, 4, 6, and 8 show the high intensity ratio of $R_{\text{CI}/\text{CO}}$ at the edge of the ring. The profiles of the CO lines mostly correspond each other at all spots, but those of C I at spots of high $R_{\text{CI}/\text{CO}}$ have different velocity features from those of CO. The different spectral profiles at the high $R_{\text{CI}/\text{CO}}$ suggest that C I traces different gas from that traced by the CO lines. In the high $R_{\text{CI}/\text{CO}}$ at the edge of the ring, [C I] would trace dark CO, e.g., an early stage of chemical evolution (Tanaka et al. 2011), although other models including the PDR model cannot be excluded. In order to clarify the reason of the different spectral profiles, multi-wavelength observations with high angular resolution enough to resolve individual molecular clouds ($\lesssim 10$ pc) are needed, since PDR models are developed to represent the structure of an individual cloud.

3.2 [C I] outflow in circum nuclear disk (CND)

Figure 4(b) shows the position-velocity (PV) diagram of [C I] along the minor axis with $PA = 28^\circ$ of NGC 613 [figure 4(a)], superposed on the PV diagram of CO(3–2). The gas motion in NGC 613 is counterclockwise and the southern part of NGC 613 is on the near side (figure 1(b), Burbidge et al. 1964). In the southern region ($Y \sim -1^\prime 0$), we found some compact components (A, B, and C) whose size of $\sim 0.4^\prime$ (34 pc) and velocity width of $\sim 10$ km s$^{-1}$, being consistent with those of GMC (e.g., Sanders et al. 1985). Especially, the location of component B at $Y \sim -1^\prime 0$ (= 85 pc) is close to the peak of the southern bubble traced by 4.9 GHz continuum, whose flux density is dominated by synchrotron emission due to the nuclear jets (Hummel & Jörsäter 1992). The [C I] intensities of 31.4, 41.7, and 14.7 K km s$^{-1}$ of components A, B, and C correspond to the column densities of $N_{\text{CI}} = 5.4$, 7.2, and $2.5 \times 10^{17}$ cm$^{-2}$, respectively, according to Ikeda et al. (2002) and $\tau_{\text{CI}} \sim 0.6$ in the CND. The ratio of $N(\text{C I})/N(\text{CO})$ in the ring becomes $\sim 0.1$, where we adopted $N(\text{CO}) = 7.0 \times 10^{16} \int T_b(\text{CO}) dV/[1 - \exp(-\tau_{\text{CI/CO}})]$ [cm$^{-2}$] by assuming $T_b(\text{CO}) \sim 12$ K and $[^{12}\text{CO}]/[^{13}\text{CO}] = 60$ (cf. Ikeda et al. 2002). We roughly estimated molecular gas masses of components A, B, and C to be 7.7, 10.2, and $3.6 \times 10^4 M_\odot$, respectively, with manners similar to Israel & Baas (2001), but adopting typical value of $[\text{C I}]/[\text{H}]/[\text{H}] \sim 1.5 \times 10^{-3}$ (e.g., Israel & Baas 2001, Israel & Baas 2003).

The molecular clouds may expand spherically because of the symmetric velocity patterns of the components and edge relative to $V_{\text{sys}}$ in figure 4(b). We assumed that the velocity difference of the edge to $V_{\text{sys}}$ is the same as the expanding velocities of all components, $v_{\text{exp}} \sim 35[= (1510 - 1440)/2]/(\cos i_{\text{out}})$ km s$^{-1}$, where $i_{\text{out}}$ is an angle between a normal line to the bubble and the line of sight. The offset between the averaged velocity of the edge and $V_{\text{sys}}$ could be caused by an inclination of the outflow to the line-of-sight, although the velocity resolution of $\Delta V = 10$ km s$^{-1}$ is not enough to discuss further. For the height of the component B of $\sim 85$ pc and the expanding velocity of $v_{\text{exp}} \sim 35$ km s$^{-1}$ as a lower limit, the expanding time is $t_{\text{exp}} \sim 2.4$ Myr, and the mass outflow rate of only component C becomes $dM_{\text{H}_2}/dt \sim 0.04 M_\odot$ yr$^{-1}$, which is higher than SFR in the CND, 0.02 $M_\odot$ yr$^{-1}$ (Falcón-Barroso et al. 2014). It is noted that the mass outflow rate in nearby starburst galaxies is comparable to SFR, e.g., M82 (Salak et al. 2014).
The AGN bolometric luminosity of NGC 613 is a few $10^{42}$ erg s$^{-1}$, accounting for $\sim 10\%$ of total luminosity including contribution of shock excitation and star formation (Davies et al. 2017). In addition, the Eddington luminosity is $L_{\text{edd}} = 1.3 \times 10^{45}$ erg s$^{-1}$ by adopting the expected BH mass of $\sim 10^7 M_\odot$ (Beifiori et al. 2012). The kinetic energy and luminosity of the outflowing component become $1/2 M_{\text{H}_2} v_{\text{exp}}^2 \sim 1.2 \times 10^{51}$ erg and $1/2 dM_{\text{H}_2}/dt v_{\text{exp}}^2 \sim 1.7 \times 10^{37}$ erg s$^{-1}$, respectively. The jet power of $P_{\text{jet}} = 1.5 \times 10^{42}$ erg s$^{-1}$, which can be estimated by adopting the central 1.4 GHz luminosity of total luminosity $3.98 \times 10^{37}$ W Hz$^{-1}$ (Hummel et al. 1985) to a scaling relation suggested by Cavagnolo et al. (2010), is larger than the kinetic luminosity. The ratio of $P_{\text{jet}}/L_{\text{edd}} = 1.2 \times 10^{-3}$ is consistent with a value expected from a numerical simulation, in whose range the jet can drive the interstellar medium efficiently (Wagner et al. 2012). These results indicate that the jet contributes driving the gas outflow, although the [C\text{II}] outflow is tentative. In order to confirm the outflow, more sensitive [C\text{II}] observations are needed.

Acknowledgments

This paper makes use of the following ALMA data: ADS/JAO. ALMA#2015.1.01487.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) and KASI (Republic of Korea), in cooperation with the Republic of Chile. The Joint ALMA Observatory is operated by ESO, AUI/NRAO and NAOJ. This work was financially supported by Grants-in-Aid for Scientific Research (KAKENHI) of the Japanese society for the Promotion of Science (JSPS, Grant No. 16H03961).

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