ALMA Observations of Multiple CO and C Lines toward the Active Galactic Nucleus of NGC 7469: An X-Ray-dominated Region Caught in the Act

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Abstract

We used the Atacama Large Millimeter/submillimeter Array to map [12]CO(J = 1−0), [12]CO(J = 2−1), [12]CO(J = 3−2), [13]CO(J = 2−1), and [C I](P 3−P 0) emission lines around the type 1 active galactic nucleus (AGN) of NGC 7469 (z = 0.0164) at ~100 pc resolutions. The CO lines are bright in both the circumnuclear disk (central ~300 pc) and the surrounding starburst (SB) ring (~1 kpc diameter), with two bright peaks on either side of the AGN. By contrast, the [C I](P 3−P 0) line is strongly peaked on the AGN. Consequently, the brightness temperature ratio of [C I](P 3−P 0) to [13]CO(2−1) is ~20 at the AGN, as compared to ~2 in the SB ring. Our local thermodynamic equilibrium (LTE) and non-LTE models indicate that the enhanced line ratios (or C I enhancement) are due to an elevated C0/CO abundance ratio (~3−10) and temperature (~100−500 K) around the AGN as compared to the SB ring (abundance ratio ~1, temperature ~100 K), which accords with the picture of the X-ray-dominated region. Based on dynamical modelings, we also provide CO(1–0)-to- and [C I](P 3−P 0)-to-molecular mass conversion factors at the central ~100 pc of this AGN as αCO = 4.1 and α[C I] = 4.4 M⊙(K km s−1 pc2)−1, respectively. Our results suggest that the C I enhancement is potentially a good marker of AGNs that could be used in a new submillimeter diagnostic method toward dusty environments.

Unified Astronomy Thesaurus concepts: AGN host galaxies (2017); Seyfert galaxies (1447); Astrochemistry (75); Interstellar medium (847); Starburst galaxies (1570); Active galactic nuclei (16)

1. Introduction

The cold gas, particularly in the molecular phase in the centers of galaxies, plays a key role in the evolution of galaxies because it is the site of massive star formation, as well as the reservoir of fuel for central supermassive black holes (SMBHs). The mass accretion onto an SMBH produces enormous amounts of energy observable as an active galactic nucleus (AGN), which is much more efficient in producing X-ray radiation than massive stars (Hickox & Alexander 2018). Consequently, we would expect that such a different heating mechanism would produce different signatures on the circumnuclear gas properties (Meijerink & Spaans 2005; Meijerink et al. 2007). For example, photodissociation regions (PDRs) caused by intense ultraviolet (UV) radiation from massive stars (e.g., Hollenbach & Tielens 1997, 1999) likely give way to X-ray-dominated regions (XDRs), where gas physical and chemical properties are governed by the harsh X-ray irradiation from the central AGN (e.g., Lepp & Dalgarno 1996; Maloney et al. 1996). Cosmic rays from supernovae and the injection of mechanical energy induced by AGN jet/outflow also make unique chemical compositions (e.g., Meijerink et al. 2011; Kazandjian et al. 2012, 2015).

Diagnosing these energy sources by submillimeter spectroscopic observations can be useful to uncover dust-obscured activity because these wavelengths do not suffer from severe dust extinction. For example, so-called obscured (total obscuring column NH ~ 1023 cm−2) AGNs account for ~50% of the total AGN population, at least at z ~ 0−2 (Buchner et al. 2015).

Hence, robust millimeter/submillimeter energy diagnostics are quite beneficial to obtain a comprehensive picture on, e.g., the cosmic evolution of SMBHs.

Based on these interests, many key molecules have been suggested as useful observational diagnostic tools. Among them, an enhanced HCN intensity relative to those of CO, HCO+, or CS (e.g., Tacconi et al. 1994; Kohno et al. 2001; Kohno 2005; Imanishi et al. 2007, 2016; Krips et al. 2008;
Izumi et al. (2013) may be a unique feature to AGNs. Extensive modeling of the observed line ratios suggest that an enhancement of HCN abundance would be a key to explain the intensity enhancement (Izumi et al. 2016b), which accords with the X-ray-induced chemistry (Lepp & Dalgarno 1996; Maloney et al. 1996) or the chemistry rather generally expected in high-temperature regions (Harada et al. 2010, 2013), although there are counterarguments for the reliability of this HCN enhancement in AGNs (e.g., Costagliola et al. 2011; Privon et al. 2020). One difficulty of studying this HCN enhancement is the interpretation of the ratio from the perspectives of line excitation, opacity, and particularly the complex (time-dependent) chemistry as discussed in Izumi et al. (2016b). Maser amplification of HCN intensity due to infrared pumping may also matter (Matsushita et al. 2015). Hence, while keeping further investigation on the robust origin of the HCN enhancement, another effort to explore alternative—and simpler to interpret, if possible—submillimeter diagnostic methods is valuable.

Given this situation, here we focus on the submillimeter atomic carbon emission line [C II] (ν=1→0) (hereafter [C II] (1→0)) at the rest frequency of ν_{rest} = 492.1607 GHz. Because of the high abundance of C^0 atoms and low energies of their fine structure levels from the ground state, the two lines of the [C II] triplet are an important coolant of the neutral interstellar medium (ISM). As C^0 is a very fundamental form of the carbon-bearing species, related formation and destruction processes are relatively simple to understand. In a classical PDR scheme, C^0 atoms distribute in a thin layer between a fully ionized H II region and a molecular core (Hollenbach & Tielens 1997, 1999). More recent refinements reached a general conclusion that C^0 rather coexists with molecular CO due to, e.g., turbulent mixing (Glover et al. 2015), nonequilibrium chemistry (Stoerzer et al. 1997), influence of cosmic rays (Papadopoulos et al. 2004, 2018), or clumpiness (Meixner & Tielens 1993).

This global spatial comconitance has been confirmed in Galactic star-forming regions (e.g., Keene et al. 1997; Ikeda et al. 1999, 2002; Plume et al. 2000; Shimajiri et al. 2013). Although PDR surfaces cannot be resolved, such similar spatial distributions are also found in nearby starburst (SB) galaxies (Krips et al. 2016; Salak et al. 2019). These consequently constitute the basis for the use of [C II] (1→0) as a potential tracer of H_2 mass, and the line is now enthusiastically observed both in nearby (e.g., Papadopoulos & Greve 2004; Kamenetzky et al. 2012; Israel et al. 2015; Jiao et al. 2017, 2019; Crocker et al. 2019) and high-redshift galaxies (e.g., Papadopoulos et al. 2004; Walter et al. 2011; Alaghband-Zadeh et al. 2013; Bothwell et al. 2017; Popping et al. 2017; Valentino et al. 2018, 2020; Nesvadba et al. 2019; Heintz & Watson 2020).

Note, however, that there is a distinct difference in, for example, the [C II] (1→0)/^{13}CO(1→0) ratio between Galactic star-forming clouds and SB galaxies. Central regions of nearby SB galaxies show [C II] (1→0)/^{13}CO(1→0) ~ 0.1–0.3 (brightness temperature T_B, Gerin & Phillips 2000; Krips et al. 2016), whereas it is usually ≤0.1 in Milky Way objects (e.g., Wright et al. 1991; Ojha et al. 2001; Oka et al. 2005), except for the harsh central molecular zone with ~0.1–0.3 (Ojha et al. 2001). Hence, the pertaining physical or chemical conditions would be different among these Galactic clouds and SB galaxies.

As compared to PDRs, the higher column-penetrating power and dissociating/ionizing nature of X-rays will more efficiently enhance C^0 abundance in XDRs relative to CO over a larger volume of molecular clouds, as the CO molecule is easily dissociated therein (Meijerink & Spaans 2005; Meijerink et al. 2007). Although most of the previous [C II] (1→0) observations toward extragalactic objects were conducted with ground-based single-dish (SD) telescopes or the Herschel Space Observatory that mixed up a few kpc scale emission (e.g., Gerin & Phillips 2000; Israel et al. 2015; Valentino et al. 2018), Israel & Baas (2002) showed that the ratio of [C II] (1→0) to ^13CO(2→1), both of which would be optically thin, depends on the type of a galaxy: it is lowest for quiescent galaxies (~0.5–1), moderate in SB galaxies (~1–3), and highest for AGN host galaxies (~4–5). The high [C II] (1→0)/^{13}CO(2→1) ratio of ~1–5 (T_B), which is usually not seen in PDRs of our Galaxy (Keene et al. 1997), is at least partly attributed to elevated C^0 abundances in extragalactic nuclei via radiative transfer calculations. More recently, Izumi et al. (2018) found in the Circinus galaxy that the [C II](1→0)/CO(3–2) flux ratio increases significantly when it is measured closer to the AGN position based on ALMA observations, indicating an influence of the AGN on the nature of the surrounding cold gas.

It is remarkable in this context that one-zone PDR and XDR models of Meijerink & Spaans (2005) show that the [C II] (1→0)/^{13}CO(2→1) ratio can be >10× higher in XDRs than in PDRs (Meijerink et al. 2007) due to the more efficient CO dissociation and harsher excitation conditions in the former. However, such a distinct difference between AGNs and SB galaxies was not observed in the SD observations of Israel & Baas (2002). This could be due to their insufficient resolution to isolate XDRs, which have a characteristic size (diameter) of ~100 pc or ~15″ in the nearby universe (Schleicher et al. 2010).

We thus need high-resolution comprehensive observations of the C^0 and CO lines to faithfully measure line flux (or abundance) ratios in XDRs, which then give a robust basis for the [C II] (1→0)-based diagnostics. Now this can be accomplished by the Atacama Large Millimeter/submillimeter Array (ALMA), which provides unprecedented high angular resolutions and sensitivities.

1.1. The Target Galaxy: NGC 7469

In this work, we present high-resolution ALMA observations of multiple CO and [C II] (1→0) lines toward NGC 7469 (Figure 1) to study detailed line emission distributions and flux ratios, with particular attention on the [C II] (1→0)/^{13}CO(2→1) ratio. An active barred spiral galaxy, NGC 7469 is located at D = 71.2 Mpc (z = 0.01641 and 1″ = 334 pc). It hosts a luminous type 1 Seyfert nucleus with an absorption-corrected 2–10 keV luminosity of L_{2–10keV} = 1.5 × 10^{43} erg s^{-1} (Liu et al. 2014), as evidenced by broad Balmer emission lines (Peterson et al. 2014). The time variability in the UV to X-ray bands (Kris et al. 2000; Nandra et al. 2000), as well as fast ionized outflows emanating from the nucleus (Blustin et al. 2007; Cazzoli et al. 2020), confirm the genuine existence of an AGN in this galaxy. Owing to its high IR luminosity (L_{8–1000μm} = 10^{11.6} L_☉), Sanders et al. 2003), NGC 7469 is also categorized as a luminous infrared galaxy (LIRG). There is an ~300 pc diameter circumnuclear disk (CND) at the center (e.g., Davies et al. 2004; Izumi et al. 2015), which is surrounded by a luminous SB ring with a radius of ~500 pc (e.g., Soifer et al. 2003).
The gray scale and contours only indicate counts. We extracted these data from the HST Legacy Archive. The regions of our interest, the SB ring and the CND, are encompassed by the red circle (r = 2′). The fields of view of our ALMA observations are indicated by the blue dashed circles (smallest one = Band 8 field of view, then becomes larger for Band 7, 6 ...). Note that the central pixel (AGN) is saturated; hence, the bar-like structure inside the red circle is an artifact.

Díaz-Santos et al. 2007). The relevant properties of NGC 7469 are summarized in Table 1.

In the CND, multiwavelength observations at centimeter (Lonsdale et al. 2003), K-band (Genzel et al. 1995), and 3.3 μm polycyclic aromatic hydrocarbon features (Imanishi & Wada 2004; Esquej et al. 2014) all indicate that the AGN is energetically dominant. Reverberation mapping observations revealed that the mass of the central SMBH is \( M_{\text{BH}} \approx 1 \times 10^7 M_\odot \) (Peterson et al. 2014), with an Eddington ratio of \( \sim 0.3 \) (Petrucci et al. 2004). The SB ring is incredibly bright at various wavelengths, including centimeter (Wilson et al. 1991; Orienti & Prieto 2010), submillimeter (Izumi et al. 2015; Imanishi et al. 2016), far-infrared (FIR; Papadopoulos & Allen 2000), mid-infrared (MIR; Soifer et al. 2003; Díaz-Santos et al. 2007), near-infrared (NIR; Genzel et al. 1995; Scoville et al. 2000), and optical to UV (Malkan et al. 1998; Díaz et al. 2000; Colina et al. 2007), with an area-integrated star formation rate (SFR) as high as \( \sim 30-50 M_\odot \) yr\(^{-1} \) (Genzel et al. 1995; Pereira-Santaella et al. 2011). By jointly analyzing the multiwavelength data, Díaz-Santos et al. (2007) revealed that many dusty, young (<100 Myr), and massive star clusters (individual mass \( \sim 10^5-10^6 M_\odot \)) are embedded in the ring. Furthermore, low-J CO observations revealed the existence of a large amount of cold molecular gas (>\( 10^5 M_\odot \)) in the central \( \lesssim 2 \) kpc region (Meixner et al. 1990; Davies et al. 2004). We have secured efficient submillimeter observations toward this object thus far, indicating abundant molecular gas (Fathi et al. 2015; Izumi et al. 2015, 2016a). Therefore, NGC 7469 provides an optimal site to simultaneously investigate how AGNs and SBs influence their surrounding gas when observed at high resolutions and may also serve as a local template to better understand the ISM properties of high-redshift quasars.

The structure of this paper is as follows. In Section 2, we describe our ALMA observations. Section 3 shows the results of our observations, including spatial distributions of the line emission, line profiles, and line ratios. We will discuss the possible origins of the enhanced ratios of [C I](1−0) to CO lines in Section 4. A conversion factor from [C I](1−0) or CO(1−0) luminosity to H2 mass in the CND is also presented there. Our conclusions are summarized in Section 5.

### Table 1

| Parameter | Value | Reference |
|-----------|-------|-----------|
| RC3 morphology | (R′)SAB(rs)a | (1) |
| Position of the nucleus | | (2) |
| Position angle (deg) | 128 | (3) |
| Inclination angle (deg) | 45 | (3) |
| Systemic velocity (km s\(^{-1}\)) | 4920 (\( \pm 0.01641 \)) | (2) |
| Distance (Mpc) | 71.2 | |
| Linear scale (pc arcsec\(^{-1}\)) | 334 | |
| Nuclear activity | Seyfert 1 | (4) |
| \( L_{2.1-10\,\mu m} \) (erg s\(^{-1}\)) | \( 1.5 \times 10^{43} \) | (5) |
| \( L_{\text{IR}} \) (\( L_\odot \)) | \( 4 \times 10^{6} \) | (6) |
| \( (\text{SFR})/(\text{CND}) \) (\( M_\odot \) yr\(^{-1} \) kpc\(^{-2}\)) | 50–100 | (7) |
| Stellar age (CND) (Myr) | 110–190 | (7) |

**Note.** The (SFR)/(CND) indicates the average SFR over the central \( \sim 1^\prime \) region. The stellar age is also measured for the CND. Kinematic parameters are derived based on CO observations. (1) de Vaucouleurs et al. (1991), (2) this work, (3) Davies et al. (2004), (4) Osterbrock & Martel (1993), (5) Liu et al. (2014), (6) Sanders et al. (2003), (7) Davies et al. (2007).

### Table 2

| Line | \( \nu_{\text{rest}} \) (GHz) | \( E_u/E_g \) (K) | \( A_{\text{ul}} \) (s\(^{-1}\)) | \( n_u \) (cm\(^{-3}\)) |
|------|-----------|-------------|----------------|----------------|
| \(^{12}\text{CO}(1–0)\) | 115.2712 | 5.5 | \( 7.20 \times 10^5 \) | \( 2.1 \times 10^2 \) |
| \(^{13}\text{CO}(2–1)\) | 220.3987 | 15.9 | \( 6.04 \times 10^7 \) | \( 9.7 \times 10^6 \) |
| \(^{12}\text{CO}(2–1)\) | 230.5380 | 16.6 | \( 6.91 \times 10^7 \) | \( 1.1 \times 10^7 \) |
| \(^{12}\text{CO}(3–2)\) | 345.7960 | 33.2 | \( 2.50 \times 10^6 \) | \( 3.6 \times 10^6 \) |
| [C I](1−0) | 492.1607 | 23.6 | \( 7.88 \times 10^8 \) | \( 1.2 \times 10^9 \) |

**Note.** Values are adopted from the LAMDA database (Schöier et al. 2005). Here \( E_u \) and \( E_g \) are the upper energy level from the ground state and the Boltzmann constant. The critical densities are calculated for \( T_{\text{gas}} = 100 \) K in the optically thin limit simply as \( n_u = A_{\text{ul}}/C_{\text{ul}} \), where \( A_{\text{ul}} \) and \( C_{\text{ul}} \) are the Einstein A- and C-coefficients of a \( u \rightarrow l \) transition. We only considered \( H_2 \) as a collision partner.

### 2. Observations and Data Reduction

Our aim with this program is to investigate detailed feedback of AGN and SB activity on their surrounding medium. We observed multiphase gas lines, including the molecular lines \(^{12}\text{CO}(1–0)\), (2–1), and (3–2); an optically thin isotopologue, \(^{13}\text{CO}(2–1)\); and the atomic carbon [C I](1–0) line, as well as their underlying continuum emission, by using ALMA. The relevant excitation parameters of these lines can be found in Table 2. Our observations were conducted during Cycle 5 (project ID: No. 2017.1.00078.S; PI = T. Izumi) using the Band 3, 6, 7, and 8 receivers from 2017 December to 2018 September. The phase-tracking center of a single pointing was set to \( (\alpha_2000.0, \delta_2000.0) = (23^h03^m15^s, +08^d52^m26^s) \), which was based on our previous ALMA observations at...
As the same issues in the calibration process. The Atacama Compact Array configuration data of the Band 7 observations, as it would have been employed in the Band 8 observations for the same purpose; we did not include the total power array observations instead adopted robust weighting. We applied the robust parameter of 0.0 to the Band 6, 7, and 8 data sets, which resulted in angular resolutions of ~0.′′34–0.′′37. As the same robust parameter produced a much higher resolution for the Band 3 data, we instead adopted robust = +0.5 with further tapering.

Band 7 (Izumi et al. 2015). Each receiver was tuned to cover one of the abovementioned lines in the two-sideband dual-polarization mode. Each spectral window has a bandwidth of 1.875 GHz, and two windows were placed on each sideband (upper and lower) to achieve a total frequency coverage of ~7.5 GHz. We used two configurations of 12 m arrays in the Band 3–7 observations so that we can both acquire high angular resolutions sufficient to separate the SB ring (radius ~1″5) from the CND (radius ~0″5) and recover the bulk of the emission extending over the central ~a few arcseconds scale. Note, however, that we decided not to use the compact configuration data of the Band 7 observations, as it would have issues in the calibration process. The Atacama Compact Array (ACA) was employed in the Band 8 observations for the same purpose; we did not include the total power array observations in this program. These result in nominal maximum recoverable scales of our observations larger than 10″. Owing to this, as well as to the fact that we will focus on line ratios measured in several CO- or continuum-bright knots (i.e., compact structures), we do not consider the effect of missing flux in this work. Further details of our observations are summarized in Table 3.

The reduction and calibration were done with CASA version 5.4 (McMullin et al. 2007) in the standard manner by using the CASA pipeline. The continuum emission was identified and subtracted in the u-v plane for each visibility set of different array configurations, and the resultant visibilities were properly combined by the task concat. All of the images presented in this paper were reconstructed using the task clean with the Briggs weighting. We applied the robust parameter of 0.0 to the Band 6, 7, and 8 data sets, which resulted in angular resolutions of ~0″34–0″37. As the same robust parameter produced a much higher resolution for the Band 3 data, we instead adopted robust = +0.5 with further tapering.
We then regard this circular region to those measured at the central, and the displayed errors indicate only statistical ones. The 13CO lines (Leroy et al. 2008, 2013) are frequently used as a tracer of bulk molecular gas due to their low intensities of 13CO relative to 12CO have been observed in SB systems with high FIR luminosities (e.g., Aalto et al. 1991, 1995; Henkel et al. 1998). As discussed in Miyamoto et al. (2018) for the case of the low-luminosity AGN NGC 613, we consider this faintness of 13CO (2–1) in NGC 7469 to be due to the low optical depth of the emission (see Section 4.1.2), not to either SB-induced selective photodissociation or nucleosynthesis (e.g., Langer et al. 1984; van Dishoeck & Black 1988; Matsushita et al. 1998). The latter two processes are inconsistent with the significantly lower star formation activity in the CND than in the SB ring (Esquej et al. 2014).

In Figure 2(f), we also show the distribution of the 860 μm (Band 7) continuum emission, which defines four representative positions (A–D) to measure line fluxes and extract spectra. The coordinates of these positions are listed in Table 6. Position A coincides with the peak position of the Very Large Array 8.4 GHz (3.5 cm) continuum emission (Condon et al. 1991; Orienti & Prieto 2010) within ~0″1. We then regard this 860 μm peak position as the AGN position of NGC 7469. The 860 μm continuum distribution in the SB ring appears quite consistent with those of the MIR (Soifer et al. 2003), indicating that it traces thermal dust emission heated by young stars. Note, however, that we would need careful modelings of the continuum spectral energy distribution (SED) at position A to reveal its exact origin, as nonthermal synchrotron emission can be a severe contaminant even at Band 7, as observed in other galaxies (e.g., García-Burillo et al. 2014). Such modeling will be presented elsewhere.

In the SB ring, all line emission distributions peak at roughly the same position as the 860 μm continuum emission, suggesting that these are star-forming giant molecular clouds (GMCs). On the other hand, there is a clear difference inside the CND between the CO lines (both 12CO and optically thinner 13CO) and [C I]1–0. The [C I]1–0 distribution clearly peaks at the exact AGN position, whereas the CO lines have two bright knots at ~0″2 north and south of the AGN. This is not due to slightly mismatched resolutions between the CO cubes and the [C I]1–0 cube. Indeed, we still see the same spatial difference after convolving the resolutions to a common 0″38 (Figure 3). Such a difference has not been the case in Galactic molecular clouds (e.g., Keene et al. 1997; Plume et al. 2000; Ikeda et al. 2002) or nearby SB galaxies (Krips et al. 2016; Salak et al. 2019), where global [C I]1–0 distribution resembles that of low-J CO lines. As this resemblance provides the backbone for [C I]1–0 as a molecular mass tracer, our result may call into question its reliability near AGNs. Note that this relative faintness of the CO lines at the AGN positions is unlikely due to an absorption effect, considering the type 1 Seyfert geometry where the AGN is directly visible.

Moreover, as compared to the CO and 13CO lines, this [C I]1–0 emission is more centrally concentrated. For example, the relative fractions of the line fluxes measured at the central r = 0″5 circular region to those measured at the central r = 3″ region are 7.2% ± 0.4% for CO(1–0), 6.0% ± 0.2% for 13CO(2–2), 11.4% ± 0.1% for CO(2–1), 14.6% ± 0.3% for CO(3–2), and 20.0% ± 0.7% for [C I]1–0. The higher central concentration in CO(3–2) than CO(1–0) is a consequence of a higher gas excitation at the inner regions of galaxies. On the other hand, given the comparable n_H (Table 2) of CO(1–0) and amount of cold molecular gas in the CND. Contrary to this base distribution, we notice that the 13CO(2–1) emission is significantly fainter at the CND than at the SB ring. Similar low intensities of 13CO relative to 12CO have been observed in SB systems with high FIR luminosities (e.g., Aalto et al. 1991, 1995; Henkel et al. 1998). We also reconstructed five continuum maps by using each of the five data sets of different frequencies listed in Table 3. The rms values of these maps were measured in areas free of emission. By inspecting the maps, we noticed that the notable peak positions (both in the CND and the SB ring) of the Band 8 continuum map, as well as the [C I](1–0) map, are offset by ~0″08 (~20% of the synthesized beam) toward the northeast direction relative to the corresponding positions in the other maps. This is due to a phase error in the Band 8 data set, as confirmed by inspecting the position of a dedicated calibration source (quasar). For the analysis in the following, we corrected this positional offset. Note that in this work, we will use only the Band 7 (860 μm) continuum map to define representative locations to measure line fluxes. Details of the full continuum properties will be discussed elsewhere.

Throughout the paper, we use line intensities corrected for the primary beam attenuation for quantitative discussion, but this correction is not critical, as most of the emission is within r ≤ 2″ from the center, which is much smaller than the primary beams (see also Figure 1). We simply refer to the 12CO isotopologue as CO, whereas 13CO is explicitly identified. The atomic carbon species is denoted as C0, with its fine structure transition as [C I]. The pixel scale of ALMA images is set to 0″06, and the displayed errors indicate only statistical ones unless mentioned otherwise. As for the systematic error, the absolute flux calibration uncertainty is ~10% according to the Cycle 5 ALMA Proposer’s Guide.

3. Results

3.1. Spatial Distributions

We first describe the distribution of cold ISM traced by CO, 13CO, and [C I] lines. Figure 2 shows the velocity-integrated intensity maps toward a central 6″ (~2 kpc) boxy region of NGC 7469. We integrated a common velocity range of 4650–5200 km s⁻¹, which surely covers the line spectra at the nucleus (Section 3.2), without any clipping to make unbiased images by using the MIRIAD task mom. The zeroth moment is defined as I = dV ΣS, where S is the line intensity and the summation is taken over the ith velocity channel of width dV. The properties of these maps can be found in Table 5. The emission of these lines was significantly detected from both the SB ring and the CND (central ~1″), as well as the regions between or outside of them. Note that the SB ring is actually composed of two major spiral arms.

Among the multiple transitions of CO, the J = 1–0 and 2–1 lines are frequently used as a tracer of bulk molecular gas due to their low n_H, (Leroy et al. 2008, 2013). These lines are brighter at the CND than at the SB ring, manifesting a large
[C I](1–0), the significantly higher central concentration of the latter line stands out. We would need a higher gas temperature (as the upper-level energy is much higher for [C I](1–0) than for CO(1–0); Table 2) but also elevated C\(^0\) abundance around the AGN to explain this peculiar behavior. Given these different spatial distributions and central concentrations, we argue that the AGN influences the [C I](1–0) brightness, likely in the form of an XDR, as discussed in Section 4 (Maloney et al. 1996; Meijerink & Spaans 2005).

3.2. Spectra and Channel Maps

Figure 4 compares the line spectra at positions A–D measured with the common 0\(^\prime\).38 (~130 pc) aperture. Note that the flux densities of CO(1–0) and 13CO(2–1) are multiplied by certain factors to fit into the panels due to their faintness. The lines are much broader at position A (full width at zero-intensity (FWZI) ~ 450 km s\(^{-1}\)) than at B–D (FWZI ~ 150–200 km s\(^{-1}\)). The different line widths indicate a higher turbulence at position A,
where the AGN resides, than the rest positions, as well as likely higher enclosed mass within the aperture therein.

The CO and $^{13}\text{CO}$ line profiles at position A clearly deviate from a single Gaussian, having two peaks at $V_{\text{LSR}} \sim 4850$ and $4980$ km s$^{-1}$. Also, the plotted contours indicate the $[\text{C} \, \text{I}] (1-0)$ distribution (70σ, 80σ, 90σ, ..., 130σ, where 1σ = 0.245 Jy beam$^{-1}$ km s$^{-1}$). These emissions are mapped at a common 0"38 resolution. The central cross in each panel defines the AGN location (position A).

### Table 5

| Emission   | Beam (arcsec × arcsec) | rms (Jy beam$^{-1}$ km s$^{-1}$) |
|------------|------------------------|----------------------------------|
| $^{12}\text{CO}(1-0)$ | 0.36 × 0.29           | 0.034                            |
|            |                        | 0.38                             | 0.036                           |
| $^{13}\text{CO}(2-1)$ | 0.35 × 0.28           | 0.014                            |
|            |                        | 0.38                             | 0.015                           |
| $^{12}\text{CO}(2-1)$ | 0.37 × 0.30           | 0.021                            |
|            |                        | 0.38                             | 0.025                           |
| $^{12}\text{CO}(3-2)$ | 0.37 × 0.31           | 0.098                            |
|            |                        | 0.38                             | 0.118                           |
| $[\text{C} \, \text{I}] (1-0)$ | 0.34 × 0.31           | 0.227                            |
|            |                        | 0.38                             | 0.245                           |

Note. The velocity range of 4650−5200 km s$^{-1}$ was integrated to make these maps. Both the native resolution data and the common 0"38 resolution data are presented.

### Table 6

| Position | R.A. (ICRS) | Decl. (ICRS) |
|----------|-------------|--------------|
| A        | 23°03'15.617 | +08°52'26.00 |
| B        | 23°03'15.686 | +08°52'27.02 |
| C        | 23°03'15.581 | +08°52'27.45 |
| D        | 23°03'15.518 | +08°52'25.02 |

Figure 3. Close-up view of the CND. The color scales indicate (a) $\text{CO}(2-1)$ and (b) $^{13}\text{CO}(2-1)$ distributions. The 1σ rms values are (a) 0.025 and (b) 0.015 Jy beam$^{-1}$ km s$^{-1}$. Also, the plotted contours indicate the $[\text{C} \, \text{I}] (1-0)$ distribution (70σ, 80σ, 90σ, ..., 130σ, where 1σ = 0.245 Jy beam$^{-1}$ km s$^{-1}$). These emissions are mapped at a common 0"38 resolution. The central cross in each panel defines the AGN location (position A).

Figure 4. Continuum-subtracted spectra of $^{12}\text{CO}(1-0)$, (2−1), (3−2), $^{13}\text{CO}$ (2-1), and $[\text{C} \, \text{I}] (1-0)$ extracted with the common 0"38 (~130 pc) aperture placed at positions A−D (see Figure 2). Due to faintness, the $^{12}\text{CO}(1-0)$ and $^{13}\text{CO}(2-1)$ spectra are scaled by certain factors for a demonstrative purpose.
From the channel maps, it is evident that [C I](1–0) shows a rotating structure around the AGN and peaks exactly at the AGN position at $V_{\text{LSR}} \sim 4920$ km s$^{-1}$, whereas CO (2–1) does not show such a clear peak at the AGN. This velocity (4920 km s$^{-1}$) is roughly the average of the two peak velocities of the CO line profiles fitted with a double Gaussian function (see Table 7). It is also consistent with the previous estimate of the systemic velocity ($V_{\text{sys}}$) of NGC 7469 from Meixner et al. (1990), who defined $V_{\text{sys}}$ as the line center of a CO(1–0) profile (4925 km s$^{-1}$). Given the higher resolution and S/N we obtained than previous submillimeter works, as well as our suggestion that the [C I](1–0) brightness would reflect the AGN influence (Section 4.1), we decide to adopt the above $V_{\text{LSR}} = 4920$ km s$^{-1}$ ($z = 0.01641$) as an updated $V_{\text{sys}}$ throughout this work. This number is exactly the same as the $V_{\text{sys}}$ that we dynamically estimate (Section 4.2).

We determine the line peak flux density, centroid velocity, FWHM, line flux, and line luminosity by fitting a Gaussian function to the observed spectra. The results are summarized in Table 7. Here we assumed a single Gaussian profile for the lines at positions B–D, but we used a double Gaussian profile for those at position A by taking the observed profiles into account. The line luminosity is calculated as

$$L_{\text{line}} = 3.25 \times 10^7 \left( \frac{D_L}{\text{Mpc}} \right)^2 \left( \frac{\nu_{\text{rest}}}{\text{GHz}} \right)^2 \times (1+z)^{-1} \left( \frac{S \Delta V}{\text{Jy km s}^{-1}} \right),$$

where $S \Delta V$ is the line flux and $D_L$ is the luminosity distance (Solomon & Vanden Bout 2005). The line luminosity is also computed in units of $L_\odot$ as

$$\left( \frac{L_{\text{line}}}{L_\odot} \right) = 1.04 \times 10^{-3} \left( \frac{\nu_{\text{rest}}}{\text{GHz}} \right) \times (1+z)^{-1} \left( \frac{S \Delta V}{\text{Jy km s}^{-1}} \right) \left( \frac{D_L}{\text{Mpc}} \right)^2.$$

In the SB ring, each line shows comparable fluxes among positions B–D, implying similar ISM conditions therein. In terms of the line luminosity ($L_\odot$), CO(3–2) clearly overwhelms the others, and [C I](1–0) follows. The FWHM of [C I](1–0) is close to that of CO(1–0) and $^{13}$CO(2–1), i.e., the low excitation or optically thin lines. These FWHMs are smaller than those of the CO(2–1) and (3–2) lines. As the gas density is usually high ($\gtrsim 10^4$ cm$^{-3}$) in the central kiloparsec regions of galaxies (e.g., Viti et al. 2014), one potential reason for these different line FWHMs is an opacity broadening (saturation effect), as the bulk of the CO molecules can be excited to higher-J levels. In the CND (position A), there are clearly CO-weak and C$^{18}$O-prominent velocity channels at around $V_{\text{LSR}} \sim 4900$ km s$^{-1}$. Hence, special care will be required when we take line ratios at this AGN position. We found that both the lower- and higher-velocity components have comparable line fluxes and FWHMs for the cases of the CO and $^{13}$CO lines. On the other hand, the lower-velocity component, which is closer to our $V_{\text{sys}}$, is much brighter and wider for the case of the [C I](1–0) line. It is also noteworthy that the [C I](1–0) line luminosity ($L_\odot$ unit) is outstandingly high at this position, the $L_{\text{line}}$ of [C I](1–0) is $(8.2 \pm 0.2) \times 10^4 L_\odot$ after summing up both the low- and high-velocity components, while it is $(7.6 \pm 0.1) \times 10^4 L_\odot$ even after adding all of the CO and $^{13}$CO line luminosities observed here. Hence, [C I](1–0) contributes to the ISM cooling as significant as low-J CO lines, implying that the chemical composition is different at position A as compared to the other positions in the SB ring.
3.3. The [C\textsc{i}](1–0) Diagnostics

By using the results of the Gaussian fitting (Table 7), we measure line flux ratios\(^{18}\) at positions A–D. At position A, we use the combined flux of the low- and high-velocity components for simplicity. Hence, the ratios at that position reflect an averaged property over the 0\textdegree 38 (~130 pc) area. Selected channel map–based values will also be shown in the following.

Here we investigate [C\textsc{i}](1–0)/CO(2–1) (≡R\textsubscript{C\textsc{i}/CO}) and [C\textsc{i}](1–0)/\textsuperscript{12}CO(2–1) (≡R\textsubscript{C\textsc{i}/\textsuperscript{12}CO}) T\textsubscript{B} ratios based on our motivation to study XDR effects on the surrounding gas, including the dissociation of CO molecules. A dependence of R\textsubscript{C\textsc{i}/\textsuperscript{12}CO} on the environments (PDR versus XDR) has been discussed in both observational works (Israel & Baas 2002; Israel et al. 2015) and chemical models (Meijerink et al. 2007). Both the [C\textsc{i}](1–0) and \textsuperscript{13}CO(2–1) lines are expected to be at least moderately optically thin under a wide range of physical conditions that would be valid for nearby galaxies. Hence, their ratio is highly sensitive not only to excitation conditions but also to their abundances. The CO(2–1) line has an ~10\times higher n\textsubscript{e} than [C\textsc{i}](1–0) in the optically thin limit.

\(^{18}\) We express line ratios in the brightness temperature (T\textsubscript{B}) unit with the Rayleigh–Jeans approximation.
central region of the nearby SB galaxy NGC 253 (Krips et al. 2016) after assuming $T_{\text{CO}}(1-0) = T_{\text{CO}}(2-1)$. On the other hand, both ratios are significantly higher at position A. The $R_{\text{C}^1/1\text{CO}}$ and $R_{\text{C}^1/1\text{CO}_3}$ at position A are $\sim 2.5\times$ and $\sim 9\times$ higher than the values in the SB ring, respectively. In addition to these, we measured channel-based line ratios at position A—for example, at the channel of 4900 km s$^{-1}$ that shows the brightest $[\text{C}\,\text{I}](1-0)$ emission (Figure 4)—to better reflect the different line profiles we observed. Now the ratios become even higher; the $R_{\text{C}^1/1\text{CO}}$ and $R_{\text{C}^1/1\text{CO}_3}$ at position A are $\sim 4\times$ and $\sim 11\times$ higher than the SB ring values, respectively. Therefore, it is evident that the $[\text{C}\,\text{I}](1-0)$ flux is dramatically enhanced relative to the CO and $^{13}\text{CO}$ fluxes around the AGN as compared to the cases in the SB ring.

We have also listed SD-based flux ratios of NGC 7469 in Table 8, which are taken from Israel et al. (2015). These values are obtained by the Herschel satellite and the ground-based James Clerk Maxwell Telescope after matching the resolutions to the Herschel data ($\sim 35\prime$). However, as the bright sources of the molecular line emission are the CND and the SB ring (Davies et al. 2004), the SD-based ratios basically reflect the averaged ISM properties of these structures. Indeed, the SD values are intermediate between the ALMA-based values at positions A and B–D. It is therefore worth emphasizing that the $R_{\text{C}^1/1\text{CO}}$ of NGC 7469 (AGN) is $\sim 5\times$ higher than the SD-based ratio. This manifests the power and necessity of the high angular resolutions provided by ALMA to spatially separate the regions with different heating sources, in particular a compact AGN-influenced region from extended SB regions, to measure line ratios that reflect the environment properly.

To compare the observed line ratios in NGC 7469 with those of other galaxies with various nuclear activities, we again compiled the line flux data of $[\text{C}\,\text{I}](1-0)$, CO(2–1), and $^{13}\text{CO}(2–1)$ from Israel et al. (2015). The literature data were taken with ground-based SD telescopes with apertures of $>22''$ (see their Table 5), hence basically probing spatial scales of $>\text{several kpc}$. Their sample includes AGNs (NGC 1068, NGC 3079, NGC 4736, NGC 4945, M51, and the Circinus galaxy), SB galaxies (IC 10, NGC 253, NGC 660, IC 342, Henize 2-10, NGC 3628, NGC 4038, M83, and NGC 6946; these include LINER-type galaxies as well), and quiescent galaxies (NGC 278, NGC 891, and Maffei 2). Our classification of the nuclear type is based on the record in the NASA/IPAC Extragalactic Database (NED), except for IC 10 and Maffei 2; we classified these as SBs, given their high nuclear SFRs (Mateo 1998; Meier et al. 2008).

The resultant plot of $R_{\text{C}^1/1\text{CO}}$ versus $R_{\text{C}^1/1\text{CO}_3}$ is displayed in Figure 6. At first inspection, although the physical scales probed are different, one may see that some galaxies with AGN contribution tend to have higher ratios in both axes. The SB galaxies, as well as the SB ring of NGC 7469, are all clustered around $R_{\text{C}^1/1\text{CO}} \sim 0.2–0.3$ and $R_{\text{C}^1/1\text{CO}_3} \sim 2–4$; the physical and/or chemical conditions governing these regions/environments (e.g., PDR characteristics) are thus not likely to be dramatically different. While some SD-based AGN ratios are already significantly higher than those of the SB galaxies, our ALMA-based ratios of the NGC 7469 AGN, particularly the channel map–based values, are outstandingly high in both $R_{\text{C}^1/1\text{CO}}$ and $R_{\text{C}^1/1\text{CO}_3}$.

In summary, to the best of our knowledge, these high ratios of NGC 7469 (AGN), hereafter called CI enhancement, have never been observed in SB galaxies or quiescent galaxies at the spatial scales probed here. Thus, we now consider that this diagram has the potential to discriminate nuclear activities as a submillimeter energy diagnostic tool.

4. Discussion

In this section, we investigate the physical origin of the CI enhancement revealed in Section 3.3 by performing both local thermodynamic equilibrium (LTE) and non-LTE analyses of $R_{\text{C}^1/1\text{CO}}$ and $R_{\text{C}^1/1\text{CO}_3}$. The purpose of these analyses is to understand a trend of the underlying physical and/or chemical conditions to explain the CI enhancement. Further detailed non-LTE modeling with extensive comparison with chemical models will be presented in our forthcoming paper.

We will see later in this section that an elevated $^{13}\text{CO}$ abundance is required to explain the CI enhancement at the AGN position of NGC 7469. This calls attention to a canonical use of this line to measure molecular mass, particularly those at the CND scale of AGN host galaxies. Therefore, we deduce Section 4.2 to deriving a specific $[\text{C}\,\text{I}](1–0)$ to $M_{\text{H}_2}$ (and CO(1–0) to $M_{\text{H}_2}$) conversion factor based on our dynamical modeling.

4.1. Physical Origin of the CI Enhancement

4.1.1. LTE Perspective

We begin by calculating $R_{\text{C}^1/1\text{CO}_3}$ under optically thin LTE conditions to relate the flux ratio to $^{13}\text{CO}$ column density ratios ($N_{^{13}\text{CO}}/N_{\text{CO}}$). As these lines are likely optically thin or moderately opaque at the most physical conditions, and their
function of line-excitation temperature under the optically thin LTE condition. The four different curves respectively correspond to the case of \( N_{12}/N_{13} = 15 \) (solid), 10 (dashed), 5 (dotted-dashed), and 1 (dotted). (1)

\[
R_{C/13CO} = 0.006 A_{12}^2 f(T_{ex}) \times N_{12}/N_{13},
\]

with \( T_{ex} \) and \( A_{12}^2 \) denoting an excitation temperature (assumed to be common for all species) and an isotopic abundance ratio of \([12]\text{CO}/[13]\text{CO}\), respectively. Hereafter, \([X]\) means an abundance of the species \(X\). The isotopic ratio varies significantly from galaxy to galaxy and even inside a single galaxy (e.g., Milam et al. 2005). For example, \( A_{12}^2 \) (we assume that this is identical to \([12]C/[13]C\) here) is \( \sim 50-60 \) at the inner Galactic sources (Lucas & Liszt 1998), \( \sim 25 \) in the Galactic central region (Guesten et al. 1985), and \( >40 \) in nearby SB galaxies (Martín et al. 2010; Henkel et al. 2014; Tang et al. 2019). Recently, Tang et al. (2019) measured this ratio in the type 2 Seyfert galaxy NGC 1068, which has a similar AGN luminosity to NGC 7469. As it is impractical to determine the isotopic ratio in NGC 7469 with the current data set, we assume \( A_{12}^2 = 40 \) hereafter, which is roughly the same value found in NGC 1068 (\( \sim 38 \)). Note that, based on Equation (3), \( R_{C/13CO} \) linearly depends on the assumed \( A_{12}^2 \).

By using Equations (3) and (4), we calculate \( R_{C/13CO} \) as a function of \( T_{ex} \) for varying \( N_{12}/N_{13} \) in Figure 7. Under these conditions, it is evident that the \( R_{C/13CO} \) observed in the SB ring of NGC 7469 and other SB galaxies can be explained by \( N_{12}/N_{13} \lesssim 3 \), but we would need further enhanced values, e.g., \( N_{12}/N_{13} \sim \text{several to } \sim 15 \), to explain the very high \( R_{C/13CO} \) observed at the AGN position of NGC 7469. However, we emphasize that the actual ratio strongly depends on \( T_{ex} \), which is hard to constrain by using the single transition [C I](1–0) line and \( ^{13}\text{CO}(2–1) \) line in our hand.

On the other hand, we may roughly estimate the \( T_{ex} \) at positions A–D by constructing rotation diagrams (Goldsmith & Langer 1999). A rotation diagram is a plot of the column density per statistical weight of a number of molecular energy levels as a function of their energies above the ground state. From the optically thin condition, the column density of level \( u \) (\( N_u \)) is written as

\[
N_u = \frac{8\pi k_B v^2 \int T_B dV}{hc^3 A_{ud}},
\]

where \( k_B \) and \( h \) are the Boltzmann and Planck constants, and \( c \) is the speed of light. Also, from the LTE condition, \( N_u \) can be expressed as

\[
N_u = \frac{N_X}{Q(T_{ex})} g_u \exp \left( -\frac{E_u}{k_B T_{ex}} \right).
\]

where \( N_X \) is the total column density of the given species \(X\), \( Q(T_{ex}) \) is a partition function \( \sim \sum_n g_n \exp(-E_n/k_B T_{ex}) \), and \( E_u \) is the energy at level \( u \) from the ground state. Then, the logarithm of \( N_u/g_u \) versus \( E_u/k_B T_{ex} \) yields a straight line with a slope and a \( y \)-axis intercept indicative of \( T_{ex} \) (or rotation temperature \( T_{rot} \)) and \( N_X \), respectively.

By using the \( J = 1–0, 2–1, \) and \( 3–2 \) CO line fluxes at positions A–D, we constructed the rotation diagrams as shown in Figure 8. If we fit the data points by straight lines, the inferred \( T_{ex} \) are \( 18.5 \pm 3.2 \) K (A), \( 13.4 \pm 2.9 \) K (B), \( 13.1 \pm 2.5 \) K (C), and \( 12.8 \pm 3.0 \) K (D). The estimated \( T_{ex} \) is relatively higher at position A than B–D, suggesting the existence of denser and/or warmer gas at the nucleus than at the SB ring. If these CO-based \( T_{ex} \) values also hold for \(^{12}\text{CO} \) and \(^{13}\text{CO} \) excitations, our prediction on \( N_{12}/N_{13} \) ratios discussed above is valid. This would not be a very inappropriate speculation given the similar excitation conditions of the lines considered here (Table 2). Thus, \( N_{12}/N_{13} \) is likely enhanced around the AGN as compared to the values at the SB ring.

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19 But see also Martín et al. (2019) for a smaller value of \( A_{12}^2 \sim 21 \) observed in the SB galaxy NGC 253.
Note, however, that the rotation temperatures derived here ought to be considered as lower limits of the true excitation and kinetic temperatures due to finite optical depths. Our rotation diagrams are already suggestive of this, as they are obviously curved. The curved feature implies that either (i) some of the lines are at least moderately optically thick or (ii) there are multiple gas components with different excitation conditions. In the case of optically thick emission (case (i)), the \( \frac{N_{\text{u}}}{g_{\text{u}}} \) value of a certain transition is underestimated by a factor of \( C_r \equiv \tau(1-e^{-\tau}) \) (Goldsmith & Langer 1999); the actual \( T_{\text{ex}} \) critically depends on this \( C_r \). In order to at least cope with this optical depth effect, we need to perform non-LTE analyses.

### 4.1.2. Non-LTE Perspective

Our non-LTE radiative transfer modelings are performed with the RADEX code (van der Tak et al. 2007) for spherical geometry to understand the underlying physical conditions of the C I enhancement, i.e., kinetic temperature \( (T_{\text{kin}}) \), \( H_2 \) volume density \( (n_{H_2}) \), and \( N_X \). RADEX uses an escape probability approximation to treat optical depth effects and solves statistical equilibrium in a homogeneous (i.e., single temperature and density), one-phase medium. Thus, we need to assume that all lines observed are emitted from the same volume, although, as we revealed in Section 3 the real structures are quite complex. Note that we do not intend to precisely model those complex environments here. The models described below are constructed for educated guesses of the relevant parameters (see similar experiments in Izumi et al. 2016b).

In our simulation, we investigated how the following parameters affect the line ratios of interest.

1. Kinetic temperature \( (T_{\text{kin}}) \). This affects the rate of the collisional excitation. The cases of 50, 100, 200, 300, and 500 K are investigated. This range mostly covers the CND-scale \( T_{\text{kin}} \) suggested for nearby AGNs and SB galaxies (e.g., Krips et al. 2008; Izumi et al. 2013; Viti et al. 2014).

2. Gas volume density \( (n_{H_2}) \). This also determines the rate of collisional excitation. The cases of \( 10^2 \), \( 10^3 \), and \( 10^4 \) \( cm^{-3} \) are studied. These are also typical values in the CNDs of nearby galaxies (e.g., Krips et al. 2008; Izumi et al. 2013; Viti et al. 2014), as well as the values that can cover the \( n_{\text{cent}} \) of our target lines (Table 2).

3. Abundance ratio. Throughout the work, we assume \( [CO]/[^{13}CO] = 40 \) (Section 4.1.1). We studied the cases of \( [C^{18}]/[CO] = 1.0, 3.0, \) and \( 10.0 \). Note that \( [C^{18}]/[CO] > 1 \) is required to reproduce \( R_{C_1/^{13}CO} > 1 \) a few according to Israel & Baas (2002).

4. Optical depth \( (\tau) \). Models with different \( N_X/\Delta V \) are used to test this effect. Here \( \Delta V \) is the line velocity width; hence, the ratio \( N_X/\Delta V \) is equivalently a ratio of a volume density of the target species to a velocity gradient over the line of sight. We set CO as our base species to consider this effect. For \( N_{^{12}CO} \), we made initial guesses from the observed CO fluxes. Applying the CO-to-\( H_2 \) conversion factor computed for the CND scale of NGC 7469 (Davies et al. 2004) to the CO(1-0) fluxes in Table 7, we obtain \( N_{H_2} = 1.4 \times 10^{23} \) \( cm^{-2} \) at position A, as well as \( N_{H_2} = (0.9-1.3) \times 10^{21} \) \( cm^{-2} \) at positions B-D. These translate into \( N_{^{13}CO} \sim 1 \times 10^{19} \) \( cm^{-2} \) if we assume a typical \( [CO]/[H_2] \) abundance ratio of \( 10^{-4} \).

Considering this \( N_{^{12}CO} \) and the observed line widths, we experimentally studied the cases of \( N_{^{12}CO}/\Delta V = 3 \times 10^{16}, 1 \times 10^{17}, \) and \( 3 \times 10^{17} \) \( cm^{-2} (km \text{ s}^{-1})^{-1} \).

5. Background temperature \( (T_{bg}) \). This affects the radiative excitation rates of the lines. While we would expect high \( T_{bg} \) particularly around an AGN, we fix this to the cosmic microwave background temperature of 2.73 K in this work for simplicity. Note, however, that this parameter potentially affects the resultant line excitation significantly, as radiative excitation sometimes becomes more important than collisional excitation (Matsushita et al. 2015; Izumi et al. 2016b). Indeed, as the upper-level energy of \([^{13}CO](1-0)\) is higher than that of \( CO(2-1) \) and \(^{13}CO(2-1)\), both \( R_{C_1/CO} \) and \( R_{C_1/^{13}CO} \) will become higher when we increase \( T_{bg} \).

The results of our radiative transfer calculations are summarized in Figure 9. It is evident that cases with higher \( N_{^{12}CO}/N_{^{13}CO} \) tend to show accordingly higher \( R_{C_1/CO} \) and \( R_{C_1/^{13}CO} \). The \( R_{C_1/^{13}CO} \) is highly sensitive to both \( T_{kin} \) and \( n_{H_2} \) in a complex manner. In the high-density cases of \( n_{H_2} = 10^2 \) and \( 10^4 \) \( cm^{-3} \), \( R_{C_1/^{13}CO} \) monotonically increases in higher \( T_{kin} \). This is due to the fast reduction of \(^{13}CO(2-1)\) opacity and intensity, as \(^{13}CO \) is easily excited to further upper rotational levels \((^{13}CO(2-1)\) is always very optically thin in these cases). As for \([^{13}CO](1-0)\), we note that its line intensity varies only slightly in each model track; although its line opacity reduces at some level, increasing \( T_{ex} \) eventually compensates for the reduction to roughly maintain the resultant \([^{13}CO](1-0)\) intensity, which leads to the enhanced \( R_{C_1/^{13}CO} \) in higher excitation conditions. On the other hand, the reduction of the \(^{13}CO(2-1)\) opacity is only moderate in the case of \( n_{H_2} = 10^3 \) \( cm^{-3} \). Hence, \(^{13}CO(2-1)\) now becomes brighter at higher \( T_{kin} \) (i.e., higher \( T_{ex} \)), which results in the reduction of \( R_{C_1/^{13}CO} \) in these low-density cases. Note that \([^{13}CO](1-0)\) is optically thin in most cases, but it can also be optically thick in limited situations, i.e., those under low excitation conditions (low \( n_{H_2} \) and \( T_{kin} \)) with large \( N_{^{12}CO}/\Delta V \sim 10^{18} \) \( cm^{-2} (km \text{ s}^{-1})^{-1} \).

The dependence of \( R_{C_1/CO} \) on the excitation conditions is complex, as our parameter space covers both optically thick and thin regimes of \( CO(2-1) \) emission. In the cases of \( n_{H_2} = 10^2 \) and \( 10^4 \) \( cm^{-3} \), \( R_{C_1/CO} \) tends to decrease for higher \( T_{kin} \), as \( CO(2-1) \) intensity increases with \( T_{ex} \) in these high line opacity cases. Contrary to this, \( R_{C_1/^{13}CO} \) tends to increase with \( T_{kin} \) when \( n_{H_2} = 10^3 \) \( cm^{-3} \). In these latter cases, the \( CO(2-1) \) intensity starts to decrease, as the line now becomes optically thinner for higher \( T_{ex} \).

Comparison of the model results in Figure 9 with the observed line ratios in Figure 6 therefore gives us insight on the prevailing physical/chemical conditions of the C I enhancement. Here we only discuss the ratios of the SB galaxies (including the SB ring of NGC 7469) and the AGN of NGC 7469\(^{20} \) for simplicity. By inspecting Figure 9, it is conceivable that \( N_{^{12}CO}/N_{^{13}CO} \sim 1 \) reproduces the ratios of the SB galaxies well, particularly when \( T_{kin} < 100 \) K, irrespective of \( n_{H_2} \). This column density ratio (or \([C^{18}]/[CO] \) abundance ratio) is fully consistent with the values measured in previous works for SB galaxies (e.g., Israel & Baas 2002; Krips et al. 2016).

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\(^{20}\) Both values from the double Gaussian fit and that of the channel map basis are discussed in the same manner here.
The interpretation of the AGN ratios is more complex, which depends on the assumed $n_{\text{H}_2}$. In the case of $n_{\text{H}_2} = 10^3$ cm$^{-3}$, we could not find a good solution within the parameter range we searched. This, in turn, suggests that the global gas density of the CND of NGC 7469 is rather high, like $\gtrsim 10^4$ cm$^{-3}$. In the case of $n_{\text{H}_2} = 10^5$ cm$^{-3}$, we need both $N_{\text{CO}}/N_{\text{CO}} \sim 10$ and $T_{\text{kin}} \gtrsim 500$ K to explain the observed high ratios. This abundance ratio is even $\sim 100 \times$ higher than those found in the Milky Way ($\sim 0.1$; Oka et al. 2005), and $T_{\text{kin}}$ is also extremely high compared to typical values of Galactic molecular clouds ($\sim 10$ K). In the higher $n_{\text{H}_2}$ cases of $10^4$ cm$^{-3}$, two possibilities arise. One is $N_{\text{CO}}/N_{\text{CO}} \sim 3$ with a high $T_{\text{kin}}$ of $\gtrsim 300$–500 K. The other is $N_{\text{CO}}/N_{\text{CO}} \sim 10$ with a bit lower $T_{\text{kin}}$ of $\sim 100$–200 K. In either case, it is required to elevate the $[C^3]/[\text{CO}]$ ratio by $\sim 3$–10$\times$ and $T_{\text{kin}}$ by $\sim 2$–10$\times$ in the NGC 7469 AGN, as compared to the SB galaxies. Therefore, both the prevalent physical and chemical conditions are clearly different between these AGN and SB galaxies.

4.1.3. What Causes the CI Enhancement?

We found that the ISM around the AGN of NGC 7469 can be characterized as showing dramatically enhanced $N_{\text{CO}}/N_{\text{CO}}$ and temperature as compared to that of SB galaxies and molecular clouds in our Galaxy. As the unique point of NGC 7469 is obviously the existence of the luminous AGN, we should attribute this enhancement to the AGN or XDR effects.

In XDRs, X-rays can directly ionize atoms and molecules deeper into the obscuring material, which can also cause doubly ionized species for heavier atoms via the Auger mechanism. The fast electrons produced by this primary X-ray ionization further cause secondary ionization, efficient gas heating due to Coulomb interaction, as well as photo-dissociation by internally generating UV photons. According to the prescription of Maloney et al. (1996), a key parameter to discuss XDR properties is the effective ionization parameter, which shapes gas temperature and chemical structures. It is expressed as

$$
\xi_{\text{eff}} = 1.26 \times 10^{-4} \frac{F_X}{n_5 N_{{\text{H}_2}}^{5.2}},
$$

where $F_X$ is the incident 1–100 keV flux in units of erg s$^{-1}$ cm$^{-2}$, $n_5$ is the gas volume density in units of $10^5$ cm$^{-3}$, and $N_{{\text{H}_2}}$ is the attenuating column density in units of $10^{22}$ cm$^{-2}$. The parameter $\phi$ is related to the photon index of an X-ray SED ($\Gamma$) as $\phi = (\Gamma + 2)/3/(8/3)$. This parameter is set to 0.9 (or $\Gamma \sim 1.8$) based on actual X-ray observations of NGC 7469 (Nandra et al. 2007). With this $\Gamma$, we also estimate the 1–100 keV luminosity of NGC 7469 as $5.6 \times 10^{43}$ erg s$^{-1}$. This X-ray luminosity is comparable to, or even larger than, the upper limit of the cosmic-ray ($>10^{18}$ eV proton) luminosity of NGC 7469 ($\sim 5 \times 10^{43}$ erg s$^{-1}$, for example, for the case of a spectral index of 2.4 and cutoff energy of $10^{20.5}$ eV for the injection cosmic-ray spectrum) measured over the whole galaxy scale (Supanitsky & de Souza 2013). Therefore, we consider that the X-rays are the prime driver of dissociation/ionization at the CND of NGC 7469.

Supposing a case of $n_5 = 1$ and $N_{{\text{H}_2}} = 10$ (typical values for CND-scale gas) for simplicity,\(^{21}\) we obtain $\log \xi_{\text{eff}} \sim -2.5$ at a

\(^{21}\) Indeed, Viti et al. (2014) obtained $n_{\text{H}_2} \gtrsim 10^{15.5}$ cm$^{-3}$ by modeling CO line ratios measured at the CND of NGC 1068.
distance of 50 pc from the nucleus; we fully covered this area with the fixed 0′′.38 aperture. According to the one-zone dense \((N_{\text{H2}} = 10^4 \text{ cm}^{-3})\) XDR chemical model of Maloney et al. (1996), we can expect \(N_{\text{CO}}^0/N_{\text{CO}} \sim 10\) and \(T \sim 300\) K for this \(\xi_{\text{eff}},\) which accords well with the results of our non-LTE analysis. Note, however, that there is a drastic increase in \(N_{\text{CO}}/N_{\text{CO}}\), and hence a correspondingly drastic decrease in \(N_{\text{CO}}/N_{\text{CO}}\) toward the region that dominantly emits \([\text{C I}](1−0))\), as the incident X-ray flux may be attenuated by intercepting the ISM before reaching a cloud of interest that is located away from the center. A sort of warping of the CND (e.g., Schinnerer et al. 2000) would also be potentially important, as it could easily alter the amount of intercepting ISM, although we do not see significant warping in the case of NGC 7469 based on our dynamical modelings (Section 4.2). In any case, it is vital to perform further higher-resolution observations to map the density structure, as well as \(\xi_{\text{eff}}\) inside this CND to robustly discuss the abundance variation (see, for example, high-resolution observations toward nearby AGNs to constrain these parameters in Kawamura et al. 2019, 2020). Even so, as XDR models can at least reproduce the observed line ratios and physical/chemical conditions we unveiled, while PDR models usually do not (e.g., Hollenbach & Tielens 1999; Meijerink & Spaans 2005), we conclude that there is indeed the influence of the AGN on the surrounding ISM in the form of the XDR.

4.2. Impact on \(H_2\) Mass Measurements

As the CND-scale gas of NGC 7469 is characterized by the extreme conditions described above, one would have concerns about how it impacts the \(H_2\) mass measurements that use CO or \(C^0\) lines. Indeed, these have been used to measure \(M_{\text{H2}}\) (or total molecular mass \(M_{\text{mol}}\)) not only in nearby AGNs but also in high-redshift quasars (e.g., Walter et al. 2011; Izumi et al. 2020), in which we certainly expect the existence of XDRs at their centers. For future high-resolution observations that directly probe the CND scale of AGNs at whichever redshift, here we try to estimate \([\text{C I}](1−0)\)- to \([\text{CO}](1−0)\)-to-\(M_{\text{H2}}\) conversion factors in NGC 7469 (CND), which will be compared with the observationally or theoretically derived values known thus far (e.g., Bolatto et al. 2013; Offner et al. 2014; Glover et al. 2015; Jiao et al. 2017).

For this purpose, we followed the scheme of Davies et al. (2004). First, we decomposed an observed velocity field to obtain the gas rotation velocity \(V_{\text{rot}}\) and dispersion \(\sigma_{\text{disp}}\), which determine the enclosed dynamical mass \(M_{\text{dyn}}\). Next, a stellar mass \((M_*)\) profile was modeled based on high-resolution Hubble Space Telescope (HST) maps. Then, we obtained a total molecular mass as \(M_{\text{mol}} = M_{\text{dyn}} - M_* - M_{\text{BH}}\), which defines the \([\text{CO}](1−0)\) and \([\text{C I}](1−0)\) conversion factors \((X_{\text{CO}}\) and \(X_{\text{C I}}\), respectively.

One big assumption is about the dominant phase of the circumnuclear gas in terms of mass. Here we assume that \(H_2\) still dominates the gas mass budget at the CND of NGC 7469, although we found that CO and \(\text{C I}\) lines are largely affected by the XDR effects, which implies that \(H_2\) (and likely \(\text{H II}\)) contribution can be significant. However, we remark that an \(\text{H II}\) column density measured by high-resolution \((0′′.38)\) radio absorption line observations toward the center of NGC 7469 is \(N_{\text{H II}} \sim 4 \times 10^{21} \text{ cm}^{-2}\) (Beswick et al. 2002). This would not represent a column density toward this type 1 AGN location, as the line-of-sight \(N_{\text{H}}\) measured with X-ray observations is \(\sim 5 \times 10^{20} \text{ cm}^{-2}\) (e.g., Kriss et al. 2000). Rather, the radio \(H_1\) absorption would take place toward bright radio continuum knot (s) in the CND (i.e., close but not identical to the AGN itself), which are found by very long baseline interferometry (VLBI) observations (Lonsdale et al. 2003). Hence, the abovementioned \(N_{\text{H}}\) of \(\sim 4 \times 10^{21} \text{ cm}^{-2}\) would represent the value at the CND. This is significantly smaller than the \(N_{\text{H}}\) tentatively inferred from our \([\text{CO}(1−0)\) observations using, for example, the Galactic \(X_{\text{CO}}\) \((N_{\text{H}} \sim 1.4 \times 10^{23} \text{ cm}^{-2};\) see footnote 20). Given these observational results, we provisionally assume the dominance of \(H_2\) (or molecular gas) in the mass budget of the region of our interest. This assumption and, consequently, the conversion factors derived here should be further verified by future high-resolution \(H_1\) mass measurements.

In the following, we use the \([\text{C I}](1−0)\) line and the \([\text{CO}(2−1)\) line cubes, both of which have sufficiently high S/N for dynamical modelings. Figure 10 shows the observed intensity-weighted mean velocity fields of these lines, defined as \((V) = \Sigma_i S_i/\Sigma_i S_i\) (moment 1) with 3\(\sigma\) clipping. The gas motion is clearly dominated by the galactic rotation with an overall northwest–southeast orientation. To extract basic beam-deconvoluted dynamical information, we fitted concentric tilted rings to the data cubes by using the 3DBarolo code (Di Teodoro & Fraternali 2015). The main parameters here are dynamical center, \(V_{\text{rot}},\) \(\sigma_{\text{disp}},\) radial motion \(V_{\text{rad}},\) \(V_{\text{sys}},\) inclination angle \((i),\) and position angle \((PA),\) all of which can be varied in each ring. However, for a better convergence, we fixed the dynamical center to the AGN position. Our initial runs returned \(V_{\text{sys}}\) fully consistent with our original estimate in Section 3. Hence, we also fixed it to 4920 km s\(^{-1}\) (optical convention); \(V_{\text{rot}},\) \(\sigma_{\text{disp}},\) \(V_{\text{rad}},\) \(i,\) and \(PA\) are thus the major parameters to fit. For initial guesses, we set \(i = 45^\circ\) and \(PA = 128^\circ\) based on the previous CO-based dynamical work (Davies et al. 2004). We modeled 50 concentric rings with \(\Delta r = 0^\circ.05\) starting from \(r = 0^\circ.10\). The fitting was evaluated by minimizing the residual amplitude, model–observed data.

The modeled mean velocity fields, as well as the residual images after subtracting the models from the observed images, are also shown in Figure 10. Most of the residual components are minor, with \(\lesssim 20\) km s\(^{-1}\) over the modeled region, which manifests the goodness of our fit. Figure 11 shows the radial profiles of the decomposed \(V_{\text{rot}}\) and \(\sigma_{\text{disp}}\). Both lines show comparable values within \(\sim 15\) km s\(^{-1}\) difference, suggesting that these trace essentially the same gas rotation in the currently observed regions. The variations in \(i\) and \(PA\) are very small (within \(5^\circ\) and \(10^\circ\), respectively) around our initial guesses.

On the other hand, we found a nonnegligible difference in \(V_{\text{rad}}\); it is within \(\pm 25\) km s\(^{-1}\) for the case of \([\text{C I}](1−0)\) over all radii, while it decreases down to \(\sim 50\) km s\(^{-1}\) (inflow) at the innermost five rings for the case of \([\text{CO}(2−1)\). However, we claim that a significant fraction of this \(V_{\text{rad}}\) is an artifact due to the configuration of the \([\text{CO}(2−1)\) emission distribution around the center, and not due to genuinely fast inflows. The two bright \([\text{CO}(2−1)\) knots appear at lower and higher velocity than \(V_{\text{sys}}\) spatially at the southwest and northeast sides of the AGN, almost along the minor axis of this galaxy (Figure 5). Owing to

\(^{22}\) Note that the Barolo code defines the PA as that of the receding half of the galaxy taken counterclockwise from the north direction on the sky. We thus need to add another 180° to the observed PA (i.e., 308°), which should be put into the code. The northern part of the galaxy is the near side to us.
this chance spatial coincidence of high- and low-velocity bright knots with the minor axis, the simple tilted-ring scheme misunderstands this configuration as caused by fast radial flows. The real $v_{\text{rad}}$ would be much milder, such as seen in the [C I](1–0) data.

Another notable feature is an upturn in $v_{\text{rot}}$ from $r \sim 1^\circ$0 to $\sim 0^\circ$5, which can be regarded as a sign of the Keplerian motion due to the central SMBH. Note that the sphere of influence (SOI) radius should be $\sim 3$ pc or $\sim 0^\circ$01 for the case of NGC 7469 with $M_{\text{BH}} = 1.06 \times 10^6 M_\odot$ (Peterson et al. 2014) and the stellar velocity dispersion of the bulge of $\sim 152$ km s$^{-1}$ (Onken et al. 2004), which is much smaller than our beam size. However, this SOI criterion does not necessarily apply for $M_{\text{BH}}$ measurements using the gas dynamical method, as shown in previous works (e.g., Davis 2014; Nguyen et al. 2019, 2020). Further detailed dynamical modeling, including the Markov Chain Monte Carlo method and the Bayesian inference to derive the $M_{\text{BH}}$ of NGC 7469, will be presented in D. Nguyen et al. (2020, in preparation).

With the decomposed value of $v_{\text{rot}}$, we compute $M_{\text{dyn}}$ as

$$M_{\text{dyn}} = \frac{r v_{\text{rot}}^2}{G} = 230 \left( \frac{r}{\text{pc}} \right) \left( \frac{v_{\text{rot}}^2}{\text{km s}^{-1}} \right)$$

where $G$ is the gravitational constant. The uncertainty of $v_{\text{rot}}$ is typically $\sim 10\%$, which propagates to the uncertainty of $M_{\text{dyn}}$. The resultant $M_{\text{dyn}}$ values are shown in Figure 12; we find very consistent values between the [C I](1–0)- and CO(2–1)-based $M_{\text{dyn}}$. The derived $M_{\text{dyn}}$ of the concentric rings is further interpolated by a fifth-order polynomial function to estimate values at a given radius. Consequently, within the $r = 0^\circ$19 or $\theta = 0^\circ$38 region where we took the line ratios (Section 3.3), we find $M_{\text{dyn}} = 2.3 \times 10^8 M_\odot$, after averaging the [C I](1–0)- and CO(2–1)-based values, which has an $\sim 15\%$ uncertainty.

As the next step, we used the HST WFC3/UVIS F547M and Advanced Camera for Surveys (ACS)/WFC F814W maps to estimate an $M_\star$ profile. Details of the HST data analysis and $M_\star$ measurements will also be presented in D. Nguyen et al. (2020, in preparation). The astrometry of these HST data was corrected by using the Gaia coordinates of NGC 7469. Here we used an empirical relation between the stellar continuum color and the mass-to-light ratio ($M/L$) developed by Bell & de Jong (2001) to measure $M_\star$. We assumed F547M $\sim V$ band and F814W $\sim I$ band, respectively, and applied the $(V-I)-to-M/L$ relation of that work. This procedure was performed in concentric elliptical annuli with the multiple Gaussian expansion model (MGE; Emsellem et al. 1994; Cappellari 2002). The Gaussians of the MGE model are then deprojected analytically with their specific axis ratios (i.e., the ratio of the semiminor axis to the semimajor axis of each concentric elliptical Gaussian) to reconstruct a three-dimensional mass distribution and calculate the enclosed mass profile (Figure 12). Note that we masked the bright central AGN ($r \leq 0^\circ$06; comparable to the FWHM of the point-spread function of the HST data = $0^\circ$08) that saturates the F814W map at that position, as well as the SB ring for our modeling. The enclosed $M_\star$ within the $r = 0^\circ$19 is $1.3 \times 10^8 M_\odot$. We found that the color variation is significant ($\sim 0.2$ mag) at $r < 10^\circ$ of NGC 7469, likely due to the complex stellar population and dust extinction, which imposes a large uncertainty on our $M_\star$. 

Figure 10. (a) Observed intensity-weighted mean velocity field of the [C I](1–0) emission in the central 7″ (~2.3 kpc) of NGC 7469. (b) Model velocity field of [C I] (1–0) using the tilted-ring method. (c) Residual velocity image after subtracting the model from the observed map. Residuals are close to 0 km s$^{-1}$ around the AGN. (a’)-(c’) Same as the top row but for the cases of CO(2–1) dynamics. In each panel, the four representative positions A–D (Table 6) are marked by crosses, and the horizontal bar corresponds to 500 pc length.
hydrogen mass is $M_{\text{H}_2} = 6.7 \times 10^7 M_\odot$ for the fractional abundance of hydrogen nuclei of 71%. Note that we do not consider the contribution of dark matter here, as we focus only on the very central region of a galaxy. The CO(1–0) and [C\textsc{i}](1–0) line fluxes and luminosities measured over that area are 1205 K km s$^{-1}$ and $2.3 \times 10^{16}$ K km s$^{-1}$ pc$^2$ for CO(1–0) and 1114 K km s$^{-1}$ and $2.1 \times 10^{17}$ K km s$^{-1}$ pc$^2$ for [C\textsc{i}](1–0), respectively (Table 7).

Therefore, the conversion factors to the total molecular mass are $\alpha_{\text{CO}} = 4.1$ and $\alpha_{\text{C}^\text{i}} = 4.4 M_\odot$ (K km s$^{-1}$ pc$^2$)$^{-1}$, respectively. The corresponding factors for the $N_{\text{H}_2}$ measurements are $X_{\text{CO}} = 1.9 \times 10^{20}$ and $X_{\text{C}^\text{i}} = 2.1 \times 10^{20}$ cm$^{-2}$ (K km s$^{-1}$)$^{-1}$, respectively. The uncertainties of the $M_{\text{dyn}}$ and $M_e$ measurements jointly yield the uncertainties of these factors, which are then $\sim 0.3$ dex, although it is hard to constrain this number accurately.

Our $X_{\text{CO}}$ is very comparable to the canonical Milky Way value (Bolatto et al. 2013; Offner et al. 2014). It is $\sim 3 \times$ larger than the typical value inferred for AGNs based on kiloparsec-scale resolution observations (e.g., Sandstrom et al. 2013) and 1.6$\times$ larger than the $X_{\text{CO}}$ previously measured for NGC 7469 itself over the central $\sim 1.7$ kpc region (Davies et al. 2004). A smaller $X_{\text{CO}}$ than the Milky Way value has been observed in nuclear regions of normal spiral galaxies as well, likely due to tidal effects on molecular clouds (Meier & Turner 2004; Meier et al. 2008). Hence, our $X_{\text{CO}}$ seems contradictory to the previously reported trend of decreasing $X_{\text{CO}}$ toward more active environments including AGNs. This is due to the high spatial resolution of this work that allows us to probe the XDR (i.e., the region at which CO molecules are dissociated to some extent) of NGC 7469 properly, which should result in a large $X_{\text{CO}}$ for a given H$_2$ mass. If this is the case, the consistency of our $X_{\text{CO}}$ with the Milky Way value is simply a chance coincidence, as the underlying physical/chemical conditions must be very different. It is noteworthy in this context that our relatively large $X_{\text{CO}}$ is consistent with the value reported by Wada et al. (2018), who simulated CND-scale CO properties around an AGN by incorporating the XDR chemical network of Meijerink & Spaans (2005). However, Wada et al. (2018) also claimed that there can be a quite large dispersion in $X_{\text{CO}}$ up to 1 order of magnitude. Therefore, similar high-resolution observations toward a statistical number of AGNs are required to assess $X_{\text{CO}}$ and its scatter at their close vicinities.

Our $C^\text{i}$ conversion factors ($\alpha_{\text{C}^\text{i}}$ and $X_{\text{C}^\text{i}}$) are $\sim 5 \times$ smaller than the values expected for Galactic star-forming clouds (Offner et al. 2014; Glover et al. 2015). Jiao et al. (2017) estimated $\alpha_{\text{C}^\text{i}} = 7.6 M_\odot$ (K km s$^{-1}$ pc$^2$)$^{-1}$ for a sample of 71 nearby U/LIRGs based on Herschel observations. Our conversion factors are still $\sim 2 \times$ smaller than this value and that individually derived for another U/LIRG, NGC 6240 (Cicone et al. 2018). The observational estimation of $X_{\text{C}^\text{i}}$ critically depends on the inverse of the $C^\text{i}$ relative abundance to H$_2$; for example, Jiao et al. (2017) assumed $[C^\text{i}]/[H_2] = 3 \times 10^{-5}$, which is a value of the $z = 2.5$ Cloverleaf quasar estimated over its galaxy scale (Weiβ et al. 2003). If the $[C^\text{i}]/[H_2]$ value for the central $\sim 100$ pc region of NGC 7469 is larger than the values of our Galactic star-forming clouds and those of U/LIRGs, our smaller conversion factors are understandable. This is again very likely the case, as we now probe the XDR of NGC 7469, where we can expect a ratio as high as $\gtrsim 10^{-4}$ according to XDR models (e.g., Maloney et al. 1996).

As our method to estimate the conversion factors is rather direct, it would be useful to estimate $M_{\text{H}_2}$ at the vicinities of AGNs. However, as the nature of an XDR is dependent on
several physical parameters, including X-ray luminosity, gas density, and attenuating column density, similar efforts to what we have performed here are required to obtain characteristic conversion factors, if they exist, and assess their scatter.

5. Summary

In this paper, we present high-resolution (∼130 pc) ALMA observations of multiple CO and C0 lines toward the central kiloparsec region of the luminous type 1 Seyfert galaxy NGC 7469. The region consists of the CND (central ∼1″) and the surrounding SB ring (radius ∼1.5″). All of the targeted emission lines, namely, CO(1–0), CO(2–1), CO(3–2), 13CO(2–1), and [C I](1–0), are successfully detected in both the CND and the SB ring. Thanks to the high resolution, we can reliably measure the line fluxes and their ratios, which are used to discuss the nature of the ISM, particularly at the vicinity of the AGN in a context of XDR chemistry. Our findings in this work are summarized in the following.

1. The 12CO lines are bright at both the CND and the SB ring, which defines the base gas distribution of this galaxy. On the other hand, 13CO(2–1) is very faint at the CND, while [C I](1–0) emission is concentrated toward the CND. The [C I](1–0) emission distribution clearly peaks at the exact AGN position, whereas the CO and 13CO distributions do not. This is unlikely to be due to the absorption effect considering the type 1 Seyfert geometry and already hints at the influence of the AGN on the gas physical/chemical structures. Given the centrally peaked distribution, the [C I] (1–0) emission also defines the systemic velocity of this galaxy as Vsys = 4920 km s⁻¹.

2. Consequently, we found that the line flux ratios of [C I] (1–0)/CO(2–1) (≡Rc/c/CO) and [C I](1–0)/13CO(2–1) (≡Rc/c/13CO), measured over an ∼130 pc area, are dramatically different between the CND and the SB ring (i.e., C1 enhancement in the CND). There is a trend of increasing these ratios in AGNs as compared to SB or quiescent galaxies, as found in the compilation of the SD-based data. But the ratios we revealed at the CND of NGC 7469 are extraordinary (Rc/c/CO ∼ 0.5 and Rc/c/13CO ∼ 20 as integrated flux ratios and Rc/c/13C0 ∼ 0.8 and Rc/c/13CO ∼ 25 as channel map-based ratios) and have never been observed at the spatial scales probed here; these AGN ratios are ∼3× and ∼10× higher than typical values of SB galaxies.

3. The high ratios observed at the CND indicate the power of the high resolution provided by ALMA, which allows us to selectively probe the regions influenced by the AGN (or likely XDR). We suggest that these ratios would have potential as a submillimeter diagnostic method of the underlying heating sources (AGN versus SB).

4. Our LTE and non-LTE analyses of the line ratios both indicate that we need an elevated C0/CO abundance ratio around the AGN as compared to that of the SB ring of this galaxy, likely by ∼3–10×, to reproduce the different line ratios observed. Moreover, we need a higher gas kinetic temperature (∼100–500 K) as well around the AGN than those at the SB ring (<100 K). Note that within the parameter range studied here, both the [C I] (1–0) and 13CO(2–1) lines are optically thin in most cases.

5. The unique abundance ratios and high gas temperature are well in accord with the scenario that the AGN influences the surrounding physical and chemical structures of the ISM in the form of an XDR.

6. We modeled the velocity fields of the [C I](1–0) line and the CO(2–1) line cubes by using a tilted-ring method. We found consistent rotation velocity (Vrot) and dispersion (σdisp) between these two lines. Using Vrot, we could measure the enclosed dynamical mass (Mcyn) inside a given radius. For example, Mcyn at r ≲ 0.019 (∼60 pc) is 2.3 × 10⁸ M☉.

7. As we revealed unusual ISM conditions around the AGN of NGC 7469, we computed dedicated conversion factors from CO(1–0) and [C I](1–0) luminosities to the total molecular (or H2) mass by also using the results of our dynamical modeling. Our big assumption is the dominance of H2 gas over the gas mass budget at the innermost ∼100 pc region of NGC 7469. We obtained αCO = 4.1 and αC1 = 4.4 M⊙ (K km s⁻¹ pc⁻²)⁻¹ for the central ∼100 pc of NGC 7469. Alternatively, XCO = 1.9 × 10²⁰ and XC1 = 2.1 × 10²⁰ cm⁻² (K km s⁻¹)⁻¹. The [C I](1–0) conversion factors of NGC 7469 are smaller than those derived for Galactic star-forming regions and nearby U/LIRGs, which would be a natural consequence of elevated C0 abundance in the XDR of NGC 7469.

The C1 enhancement captured in this work is quite a dramatic phenomenon. As it is only based on the results of NGC 7469, we will further investigate the trend by increasing the sample galaxies and extensively discuss the ISM properties by also comparing the ratios with state-of-the-art chemical models. For the particular case of NGC 7469, we guide readers to our forthcoming paper (S. Nakano et al. 2020, in preparation) for such comparisons. If the trend is confirmed, the C1 enhancement will be used as a submillimeter energy diagnostic method that is applicable to dusty environments, as this wavelength does not suffer from severe dust extinction (except for some extremely dusty cases seen in so-called compact obscured nuclei; e.g., Sakamoto et al. 2013; Aalto et al. 2019), as well as to high-redshift galaxies owing to the high vrest of [C I](1–0).

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