INTERFEROMETRIC $^{12}$CO $J = 2–1$ IMAGE OF THE NUCLEAR REGION OF SEYFERT 1 GALAXY NGC 1097

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ABSTRACT

We have mapped the central region of the Seyfert 1 galaxy NGC 1097 in $^{12}$CO $J = 2–1$ with the Submillieter Array (SMA). The $^{12}$CO $J = 2–1$ map shows a central concentration and a surrounding ring coinciding, respectively, with the Seyfert nucleus and a starburst ring. The line intensity peaks at the nucleus, whereas in a previously published $^{12}$CO $J = 1–0$ map the intensity peaks at the starburst ring. The azimuthally averaged $^{12}$CO $J = 1–0$ intensity ratio $R_{21}$ of the ring is about unity, which is similar to those in nearby active star-forming galaxies, suggesting that most of the molecular gas in the ring is involved in fueling the starburst. The ratio of molecular gas to dynamical mass in the starburst ring shows a somewhat lower value than that found in nearby star-forming galaxies, suggesting that the high $R_{21}$ of unity may be caused by additional effects, such as shocks induced by gas infall along the bar. The molecular gas can last for about $1.2 \times 10^8$ yr without further replenishment, assuming a constant star formation rate. The central gas is rotating with the molecular ring in the same direction, while its velocity gradient is steeper than that of the ring, and similar to what usually observed in Seyfert 2 galaxies. To view the Seyfert nucleus without obscuration, the central gas can be a low-inclined disk or torus but not too low to be less massive than the mass of the host galaxy, or be a highly inclined thin disk or clumpy and thick torus, inner part of the galactic disk is also possible. The $R_{21}$ of ~1.9 of the central gas is significantly higher than that of the ring, indicates that the activity of the Seyfert nucleus may significant influence the central gas.

Subject headings: galaxies: active — galaxies: individual (NGC 1097) — galaxies: ISM — galaxies: nuclei — galaxies: Seyfert

1. INTRODUCTION

NGC 1097 [SB(s)b; de Vaucouleurs et al. 1991] is a nearby, inclined (46$^\circ$; Ondrechen et al. 1989), barred spiral galaxy at a distance of $D = 14.5$ Mpc (1$''$ = 70 pc; Tully 1988). It hosts a Seyfert 1 nucleus, which is surrounded by a circumnuclear starburst ring with a radius of 10$''$ (0.7 kpc). NGC 1097 was originally identified as a LINER (Keel 1983), but over the past two decades has shown Seyfert 1 activity as evidenced by the presence of broad double-peaked Balmer emission lines (FWHM $\approx$ 7500 km s$^{-1}$; Storchi-Bergmann et al. 1993). The starburst ring is rich in molecular gas (1.3 $\times$ 10$^9$ $M_\odot$; Gerin et al. 1988), and exhibits a high star formation rate of 5 $M_\odot$ yr$^{-1}$ as estimated from its extinction-corrected H$\alpha$ luminosity (Hummel et al. 1987). A network of dusty spiral features connects the starburst ring with the nucleus (Barth et al. 1995; Prieto et al. 2005). Optical spectroscopic imaging observations show evidence for radial streaming motions associated with the spiral structures leading to the unresolved nucleus (Fathi et al. 2006).

Kohno et al. (2003) have previously mapped the central ~1$'$ of NGC 1097 in $^{12}$CO $J = 1–0$ and HCN $J = 1–0$ with the Nobeyama Millimeter Array (NMA). Their $^{12}$CO $J = 1–0$ map shows a ringlike structure consisting of several bright knots located at the starburst ring, and this molecular gas ring structure is similar to that revealed by the single-dish $^{12}$CO $J = 1–0$ observations (Gerin et al. 1988). The interferometric $^{12}$CO $J = 1–0$ map also revealed a relatively weak central concentration coincident with the nucleus. Their HCN $J = 1–0$ map shows similar knots in the starburst ring, but in contrast to their $^{12}$CO $J = 1–0$ map, a relatively bright central concentration of the HCN emission coincides with the nucleus. This implies that the molecular gas associated with the nucleus is relatively dense ($n_{hi} \geq 10^5$ cm$^{-3}$). Similar dense central gas concentrations have been reported in NGC 1068 (Jackson et al. 1993), M51 (Kohno et al. 1996), and NGC 6951 (Krips et al. 2007), all of which are type 2 Seyfert galaxies. In all these cases, the dense central gas concentrations have been attributed to a highly inclined circumnuclear molecular torus invoked by AGN unification models (e.g., Antonucci 1993) to obscure the central engine from direct view in the optical. This is the first time, however, that such a dense central gas concentration has been seen in a Seyfert 1 galaxy, warranting observations at higher angular resolutions to determine whether it is a good candidate for the hypothesized circumnuclear molecular torus.

In this paper we study the central region of NGC 1097 in $^{12}$CO $J = 2–1$ using the Submillimeter Array (SMA; Ho et al. 2004). While the previous HCN $J = 1–0$ and $^{12}$CO $J = 1–0$ interferometric observations are suitable for tracing density variations in the molecular gas, they are not suitable for studying variations in the gas temperature. If the $^{12}$CO $J = 1–0$ line is optically thin, the intensity ratio between the $^{13}$CO $J = 1–0$ line and the higher $J$ lines provides constraints on the gas temperature (and density; e.g., Matsushita et al. 2004). In addition, we observe the $^{13}$CO $J = 2–1$ line at a factor of 2–3 higher angular resolution than the previous observations in $^{12}$CO $J = 1–0$ and HCN $J = 1–0$, allowing us to examine for the first time the spatial-kinematic structure of the central gas concentration.

2. OBSERVATIONS AND DATA REDUCTION

We observed the central region of NGC 1097 in the $^{12}$CO $J = 2–1$ line (rest frequency of 230.538 GHz) with the SMA,
which has a primary beam of 52'' (3.6 kpc) at this frequency. The receivers were turned to observe the $^{12}\text{CO} J = 2 - 1$ line at the upper side band. The observations were performed on 2004 July 23 and October 1 with eight 6 m antennas in the compact configuration. The 225 GHz zenith opacity of the two observations are $\sim$0.15 and $\sim$0.3, and the $T_{\text{sys, DSB}}$ are $\sim$200 and $\sim$350 K, respectively. We placed the phase center at $\alpha = 02^{h}46^{m}18.96^{s}$ and $\delta = -30^{\circ}16^{\prime}28.897^{\prime\prime}$ (J2000.0), which corresponds to the position of the AGN defined by the intensity peak of the 6 cm continuum emission (Hummel et al. 1987). The SMA correlator has a total bandwidth of 2 GHz, and was configured to provide frequency resolution of 0.8125 MHz ($\sim$1 km s$^{-1}$) and 3.25 MHz (4.2 km s$^{-1}$) for the July 23 and October 1 observations, respectively. We observed Uranus for bandpass and absolute flux calibrations. We used J0132−169 and J0423−013 for complex gain calibrations. J0132−169 is weaker but closer to the source (21.5'' away), and was used for phase calibration only; J0423−013 is stronger but further from the source (37'' away), and used for amplitude calibration. The absolute flux uncertainty and the positional accuracy have been estimated as $\sim$15% and 0.1'', respectively, in these observations.

The observation on July 23 was binned to the same velocity resolutions as that on October 1 (3.25 MHz), and then combined with each other. The data were calibrated with the Owens Valley Radio Observatory software package MIR, which was modified for the SMA. The images were CLEANed using the NRAO software package AIPS, and with natural weighting have an angular resolution of 4.1''×3.1'' (290 pc×220 pc) at a position angle (P.A.) of 168°. The rms noise level of the individual channel maps is 75 mJy beam$^{-1}$. We used the MOMNT task in AIPS to make the integrated intensity and the intensity-weighted mean-momentum maps. The line free channels were binned to create a continuum map with a rms noise level of 4.4 mJy beam$^{-1}$; no significant emission was detected in this map.

3. RESULTS

We detected the $^{12}\text{CO} J = 2 - 1$ line spanning a total line width of $\sim$570 km s$^{-1}$ at the 3 $\sigma$ detection threshold in the channel maps. The line width is comparable to that measured in the single-dish observation (Petitpas & Wilson 2003) of $\sim$550 km s$^{-1}$ using the JCMT, which has a primary beam of 21'', although the integrated line intensity in our map is only 60% ± 13% of that measured in this single-dish observation (see § 3.3), including uncertainties of the flux in both observations.

3.1. Spatial Distribution

We show the $^{12}\text{CO} J = 2 - 1$ integrated intensity map in Figure 1a. A relatively strong molecular concentration (hereafter, central component) is detected at the very center in a region of a diameter of 350 pc (5''), surrounded by a weaker molecular ring of a diameter of 1.4 kpc (20''). The centroid of the central molecular gas component is shifted by $\sim$0.7'' from that of the radio continuum core at 6 cm, which presumably marks the location of the AGN (Hummel et al. 1987). We return to this positional difference in § 3.2.

The molecular ring coincides with the starburst ring, consistent with the previous $^{12}\text{CO} J = 1 - 0$ maps (Gerin et al. 1988; Kohno et al. 2003). Unlike the tightly wound spiral structure seen in optical maps (e.g., Rickard 1975; Barth et al. 1995), the molecular ring traces a complete circle as seen in the $J - K_s$ color map of Prieto et al. (2005). The molecular ring is composed of several knots that closely resembles the 1.5 GHz continuum map of Hummel et al. (1987). In addition, we detected weak molecular emission extending from the northeast and southwest of the molecular ring, coinciding with dust lanes along the large stellar bar (indicated by the two straight lines in Fig. 1a).

In Figure 1b we show the $^{12}\text{CO} J = 1 - 0$ map made by Kohno et al. (2003) with the NMA. As can be seen, the molecular ring is more clearly discernible and also more clearly separated in our $^{12}\text{CO} J = 2 - 1$ map than in the $^{12}\text{CO} J = 1 - 0$ map. The intensity peak in the $^{12}\text{CO} J = 2 - 1$ map is located at the nucleus, whereas that in the $^{12}\text{CO} J = 1 - 0$ map is located at the northeast part of the ring. The southwest side of the ring is brighter than the northeast side in the $^{12}\text{CO} J = 2 - 1$ map, but the reverse is true in the $^{12}\text{CO} J = 1 - 0$ map. Both of the molecular gas peaks at the northeast and southwest sides of the ring are located at the
regions where the dust lanes connect with the ring, and these molecular gas peaks are often seen in barred spiral galaxies, which are known as the twin-peak morphology (e.g., Kenney et al. 1992).

3.2. Kinematics

In Figure 2a we show the intensity-weighted $^{12}\text{CO} \ J = 2–1$ mean-velocity map. Both the central component and molecular ring show an overall velocity gradient in the northwest to southeast direction along a P.A. of 135°, that is similar to the major kinematic axis of the large-scale galactic disk (Ondrechen et al. 1989). The emission is blueshifted on the northwestern side of center, and redshifted on the southeastern side of center with respect to the systemic velocity of 1254 km s$^{-1}$ for NGC 1097 (Kohno et al. 2003). The gas motion in the molecular ring appears to be dominated by circular motion (i.e., isovelocity contours perpendicular to major axis), whereas in the $^{12}\text{CO} \ J = 1–0$ velocity map of Kohno et al. (2003) the isovelocity contours have a symmetric S-shape with the end of the S-shape nearly parallel to the dust lanes along the large stellar bar. This non-circular motion is not as prominent in our $^{12}\text{CO} \ J = 2–1$ map, perhaps because the aforementioned dust lanes are not as strongly detected in $^{12}\text{CO} \ J = 2–1$, along with the fact that they are closer to the edge of our primary beam than in the $^{12}\text{CO} \ J = 1–0$ observations of Kohno et al. (2003).

A position-velocity diagram (hereafter p-v diagram) of the $^{12}\text{CO} \ J = 2–1$ emission along its major kinematical axis (P.A. = 135°) is shown in Figure 2b. Positive and negative velocities correspond to redshifted and blueshifted velocities, respectively, relative to the systemic velocity. The rapidly rising part of the rotation curve corresponds to the central component, and the flat part to the molecular ring. The rotation curve is symmetric on both sides of the center, rising steeply to $\pm235$ km s$^{-1}$ at $\pm2.5''$ and flattening outside $\pm2.5''$. This indicates that the size of the central component is about 350 pc in diameter. As can be seen in Figure 2b, the emission from the central component is stronger on the redshifted southeastern part, causing the centroid of the emission to be shifted by 0.7'' toward the southeast as mentioned in § 3.1 (and shown in Fig. 1a). The velocity gradient of the central component is $1.31 \pm 0.14$ km s$^{-1}$ pc$^{-1}$ (Fig. 1b), which is similar with that derived in the optical from ionized gas ($1.1$ km s$^{-1}$ pc$^{-1}$; Storchi-Bergmann et al. 1996).

3.3. $^{12}\text{CO} \ J = 2–1/J = 1–0$ Line Ratios

Our $^{12}\text{CO} \ J = 2–1$ map detected about 60% of the flux measured with the JCMT (Petitpas & Wilson 2003). The shortest projected baseline in our SMA observations is 4.8 kλ ($\sim 6$ m), and so the largest structure we can detect is $\sim 52''$, comparable in size to the SMA primary beam. We therefore assume that the molecular gas resolved out in our map is uniformly distributed in space and in velocity over the entire line width, and have corrected for $\sim 40%$ of the missing flux. We applied a primary-beam correction to both the $^{12}\text{CO} \ J = 2–1$ and $^{12}\text{CO} \ J = 1–0$ maps, and convolved the derived moment maps to the same angular resolution of 6.5$'' \times 3.5''$ with P.A. of 0°. These moment maps were then used to derive the $^{12}\text{CO} \ J = 2–1/^{12}\text{CO} \ J = 1–0$ line ratios. Note that we also calculated the line ratios with unresolved data, and the ratios are consistent with the missing flux-corrected line ratios within errors. To derive the molecular gas column densities and masses, we need to use the missing flux-corrected data (see § 3.4). To make consistency within this paper, we use the missing flux-corrected data for the following calculations.

In Figure 3 we show the azimuthally averaged radial intensity distributions of the $^{12}\text{CO} \ J = 2–1$ (dashed line) and $^{12}\text{CO} \ J = 2–1$ (dotted line) lines, and the azimuthally averaged $^{12}\text{CO} \ J = 2–1/^{12}\text{CO} \ J = 1–0$ line intensity ratio ($R_{21}$; solid line). The radial intensity profile in both $^{12}\text{CO} \ J = 2–1$ and $^{12}\text{CO} \ J = 1–0$ peak at the center, corresponding to the central component, and exhibit a secondary peak at a radius of 10'', corresponding to the
molecular ring. The line ratio $R_{21}$ exhibits a similar behavior, peaking at the central component and exhibiting a secondary peak at the molecular ring. At the nucleus, $R_{21}$ is derived as 1.9 ± 0.2 at a beam size of $6.5'' \times 3.5''$, which corresponds to the approximate angular extent of the central component along its major kinematic axis. In the molecular ring, the azimuthally averaged value between radii of 8'' and 12'' is $R_{21} = 1.3 ± 0.2$.

The averaged $R_{21}$ at the molecular ring is similar to or somewhat larger than the global $R_{21}$ in spiral galaxies of ~0.7 – 0.9 (Braine et al. 1993; Lavezzi et al. 1999; Hafok & Stutzki 2003). The $R_{21}$ at giant molecular clouds (GMCs) in the nearby star-forming region Orion (Sakamoto et al. 1994) or GMC-scale $R_{21}$ in the nearby starburst galaxy M82 (Weiss et al. 2001) also shows similar $R_{21}$ of about unity. On the other hand, the $R_{21}$ at the central component is about twice as high as those in the above-mentioned sources, and consistent with the ratio reported in the Seyfert 2 galaxy NGC 1068 (Baker & Scoville 1998; Schinnerer et al. 2000b). The $R_{21}$ at the central component is also similar to that found at active star-forming regions or at the interfaces of molecular clouds and ionized gas in the nearby barred spiral galaxy IC 342 (Turner et al. 1993; Meier et al. 2000). Galactic objects, such as molecular outflows from young stellar objects (e.g., Richardson et al. 1985; Chandler et al. 1996) or molecular gas around supernova remnants (van Dishoeck et al. 1993; Seta et al. 1998), also show $R_{21} ≲ 2$. Note, however, that the high value of $R_{21}$ are not always seen in active galaxies; for instance, interferometric observations of NGC 3227 (Seyfert 1; Schinnerer et al. 2000a), NGC 3718 (LINER/Seyfert 1; Krips et al. 2005), and NGC 6574 (Seyfert 2; Lindt-Krieg et al. 2008) show $R_{21}$ of around unity.

3.4. Physical Properties of the Molecular Gas

We derived the column density of the molecular gas in the central component and molecular ring assuming the standard Galactic conversion factor of $3.0 \times 10^{20}$ cm$^{-2}$ (K km s$^{-1}$)$^{-1}$ between the $^{12}$CO $J = 1–0$ line intensity and column density of molecular hydrogen gas (Scoville et al. 1987; Solomon et al. 1987). The $^{12}$CO $J = 2–1$ integrated intensity at the center (beam size of $3.1'' \times 4.1''$) is 376.7 ± 7.2 K km s$^{-1}$. Assuming the same line ratios derived from a beam size of $6.5'' \times 3.5''$, namely, $R_{21} = 1.9 ± 0.2$ for the central component, we derive a column density for this component of $(5.9 \pm 0.6) \times 10^{22}$ cm$^{-2}$, and the molecular hydrogen gas mass of $(6.5 \pm 0.7) \times 10^{6} M_{\odot}$. In the molecular ring, the azimuthally averaged $^{12}$CO $J = 2–1$ integrated intensity between the radii of 8'' and 12'' is 135.7 ± 7.2 K km s$^{-1}$. With $R_{21} = 1.3 ± 0.2$, the azimuthally averaged column density at the molecular ring is therefore $(3.0 ± 0.3) \times 10^{22}$ cm$^{-2}$, and the molecular hydrogen gas mass is $(5.8 ± 0.6) \times 10^{6} M_{\odot}$. Here we compare our estimated molecular gas mass of the ring with that estimated using the single-dish data. We recalculated the gas mass inside 20'' in radius derived by Gerin et al. (1988) using the conversion factor mentioned above, and it is calculated as $1.1 \times 10^{6} M_{\odot}$. We then subtract the gas mass of the center from this gas mass. The gas mass of the center is calculated as $2.4 \times 10^{8} M_{\odot}$ using the central position data with a $T_{b}$ of ~32 K km s$^{-1}$ (Fig. 3 of Gerin et al. 1988). The gas mass of the ring is therefore calculated as $8.6 \times 10^{6} M_{\odot}$. This value is somewhat larger than ours, and this may be due to their larger radius of 20'', and therefore their results may be detecting emission outside the ring.

To determine the temperature and density of the molecular gas, we use the LVG method (Goldreich & Kwan 1974). We assume a one-zone model, which assumes that both the $^{12}$CO $J = 2–1$ and $^{12}$CO $J = 1–0$ emissions originate from the same region. The collision rates for CO are taken from Flower & Launay (1985) for the temperature regime $T = 10$ – 250 K, and McKee et al. (1982) for $T = 500$ – 1000 K. We first assume a standard $Z(12CO)/(dv/dr)$ of $5.0 \times 10^{-5}$ (km s$^{-1}$ pc$^{-1}$)$^{-1}$, where $Z(12CO)/[H_{2}]$ is the abundance ratio and $dv/dr$ is the velocity gradient of the molecular gas.

We then compute from the LVG model the line ratio $R_{21}$ and $^{12}$CO $J = 1–0$ opacity as a function of molecular hydrogen number density $n_{H_{2}}$, and kinetic temperature $T_{k}$ as shown in Figure 4a. The result for $R_{21} = 1.9 ± 0.2$ as inferred for the central component indicates that $T_{k} ≥ 400$ K, and $n_{H_{2}} = 3 \times 10^{4}$ cm$^{-3}$, and $^{12}$CO $J = 1–0$ opacity below unity. The density estimation is consistent with the detection of HCN $J = 1–0$ line from the central component (Kohno et al. 2003), which indicates the molecular gas density as high as $n_{H_{2}} = 10^{4}$ cm$^{-3}$. Note that the estimated kinetic temperature is highly dependent on the assumed $Z(12CO)/(dv/dr)$, namely, highly dependent on the $[12CO]/[H_{2}]$ relative abundance, on the velocity gradient, or on both. Fixing $n_{H_{2}} = 1 \times 10^{4}$ cm$^{-3}$, we plot $R_{21}$ as a function of $T_{k}$ and $Z(12CO)/(dv/dr)$ in Figure 4b. As can be seen, $R_{21}$ increases roughly linearly with $Z(12CO)/(dv/dr)$, and around the standard $Z(12CO)/(dv/dr)$ of $= 10^{-5}$ (km s$^{-1}$ pc$^{-1}$)$^{-1}$, we find that a kinetic temperature at least 100 K is required to reach $R_{21}$ of 1.9 ± 0.2. If on the other hand $Z(12CO)/(dv/dr)$ is an order of magnitude lower than the standard value (i.e., order of $10^{-5}$), the kinetic temperature would be in the range of $T_{k} ≈ 30$ – 250 K, which is comparable with the temperature range normally found in molecular clouds.

For the molecular ring, which has an average $R_{21} = 1.3 ± 0.2$, $T_{k} ≥ 100$ K and $n_{H_{2}} = 8 \times 10^{4}$ cm$^{-3}$ assuming the standard $Z(12CO)/(dv/dr)$. Again, these values are sensitive to the assumed $Z(12CO)/(dv/dr)$, and if this value decreases, $T_{k}$ and $n_{H_{2}}$ also decrease.

4. DISCUSSION

4.1. Molecular Gas in the Starburst Ring

The average $R_{21}$ of about unity in the molecular ring suggests that the overall properties of the molecular gas in the starburst...
The nuclear component is plotted as a function of ring (1 Solid lines are the number density corresponding to the width of the molecular ring) can be estimated as content in the starburst ring is, on the other hand, not as high as is actually fueling the starburst activities in the ring. The gas mass stars form from molecular gas, we believe that this molecular gas activities occurring in the ring. This is also supported by the high line ratios of the central component and its physical conditions, between the central component and the AGN activities based on the line ratios of the central component and its physical conditions, which were derived using the LVG analysis results presented in the previous section.

Our $^{12}$CO $J = 2$–1 map peaks at the nucleus, different from the $^{12}$CO $J = 1$–0 map, and the $R_{21}$ shows 1.9 ± 0.2. This value is significantly higher than the global $R_{21}$ of spiral galaxies or $R_{21}$ in star-forming GMCs in Orion or M82, but similar to the $R_{21}$ of molecular gas at jets, at supernova remnants, or at the surface between molecular gas and ionized gas (§3.3). These results suggest that the high $R_{21}$ in molecular gas can be related to irradiation of UV photons from star-forming regions, shock caused by interaction between molecular gas and outflowing, or expanding materials, but not to the global galactic characteristics or activities. Hence similar activities can be the cause of high $R_{21}$ in the central region of NGC 1097. However, other activities that cannot be seen in star-forming galaxies or in our Galaxy can also be the cause of high $R_{21}$, such as strong X-ray radiation from the Seyfert 1 nucleus (e.g., Lepp & Dalgarno 1996; Kohno et al. 2001; Usero et al. 2004; Kohno 2005; Meijerink et al. 2007).

From LVG analysis, high temperature ($T > 400$ K) and high density ($n > 3 \times 10^{4.1}$ cm$^{-3}$) conditions are derived for the central component, assuming a standard $Z(^{12}$CO)/$dv/dr$. As mentioned
in § 3.4, the density is consistent with the centrally peaked HCN(1–0) map (Kohno et al. 2003). Furthermore, these conditions are supported by results from infrared observations: Strong molecular hydrogen line, H2 1–0 S(1), is detected toward the nucleus without any detection of Brγ line, and the JHK images show red colors toward the nucleus, suggesting that the presence of hot dust coexisting with the dense molecular gas (Kotilainen et al. 2000). Such high-density and high-temperature conditions for molecular gas around Seyfert nuclei are also derived in other galaxies, such as the Seyfert 2 nucleus of M51 (Matsushita et al. 1998; Matsushita et al. 2004) or NGC 1068 (Rotaciuc et al. 1991; Tacconi et al. 1994), but not for the molecular gas in nonactive galaxies such as IC 342 or our Galaxy (Matsushita et al. 1998). These physical values are, however, sensitive to $Z(^{12}\text{CO})/(dv/dr)$, namely, to the $^{12}\text{CO}$ abundances, to the velocity gradient, or to both. As shown in § 3.4, lower $Z(^{12}\text{CO})/(dv/dr)$ makes the derived temperature lower. This is because the opacity is linearly related to $Z(^{12}\text{CO})/(dv/dr)$, and it will decrease if $Z(^{12}\text{CO})/(dv/dr)$ decreases. Under low $Z(^{12}\text{CO})/(dv/dr)$ conditions, if the temperature rises, the $^{12}\text{CO} J = 1–0$ line can easily be optically thin, and easier to have high $R_{21}$ at lower temperature than the normal $Z(^{12}\text{CO})/(dv/dr)$ condition. In either case, the molecular gas around Seyfert nuclei seems to have different properties from other normal environments, which seems to be largely related to the Seyfert activities. Combined with the spatial and kinematical information, we suggest that the central component is kinematically and physically related to the Seyfert nucleus.

4.3. Is the Circumnuclear Gas the Hypothetical Circumnuclear Torus?

Given that the central component is closely related to the AGN, is this then the circumnuclear molecular torus predicted by AGN unified models? Since NGC 1097 hosts a Seyfert 1 AGN, we expect that the rotating circumnuclear gas is in a nearly face-on configuration to provide an essentially unobscured view to the broad-line region (BLR), if we apply the general unified model for AGNs (e.g., Antonucci 1993). Kinematics of the central component we observed are, however, similar to what is usually observed in other Seyfert 2 galaxies, such as NGC 1068 (Jackson et al. 1993; Schinnerer et al. 2000b) or M51 (Kohno et al. 1996; Scoville et al. 1998); the central component shows steep velocity gradient that can be explained by edge-on disk or torus rotating around the Seyfert nucleus. In addition, we derived a molecular hydrogen column density ($N_{\text{H}_2}$) toward the nucleus of $(5.9 \pm 0.6) \times 10^{22} \text{ cm}^{-2} (§ 3.4)$, or $1.2 \times 10^{23} \text{ cm}^{-2}$ in atomic hydrogen column density ($N_{\text{H}}$), which is about 2 orders of magnitude larger than $N_{\text{H}}$ derived from X-ray spectra of $1.3 \times 10^{21} \text{ cm}^{-2}$ (Iyomoto et al. 1996; Terashima et al. 2002).

From these “inconsistent” results between our molecular gas observations and other observations at different wavelengths/frequencies, the structure of the central component can have two basic configurations; one is a nearly face-on disk-, ring-, or torus-like structure with a very fast rotation velocity, and another is a nearly edge-on disk-, ring-, or torus-like structure with a thin or clumpy structure. Due to our large synthesized beam size, we could not distinguish these two possibilities observationally, and also could not evaluate the thickness of the structure. Here we discuss the advantages and disadvantages of both possibilities.

The former molecular gas configuration has a nearly face-on structure, so the direct view to the BLR is secured. But since the observed rotational velocity width has 470 km s$^{-1}$, the inclination-corrected rotational velocity width for this configuration has to be 470 sin (i), where i is the inclination (0° corresponds to a face-on configuration). The nearly face-on configuration therefore leads to a high rotational velocity (e.g., 940 km s$^{-1}$ even for the inclination angle of 30°). Note that this rotation is rigid rotation, and it is rare to see rigid rotation velocity of >500 km s$^{-1}$ in other galaxies (e.g., Rubin et al. 1980, 1982; Sofue et al. 1999). In addition, assuming the inclination angles as 30°, 10°, and 5°, the dynamical mass within the central gas, namely, within the radius of 2.5″ (175 pc), can be estimated to be $8.8 \times 10^{10}$, $7.3 \times 10^{10}$, and $2.9 \times 10^{11} M_{\odot}$, respectively. The total dynamical mass of NGC 1097 within a radius of 7.5″ (31.5 kpc) estimated from the large-scale atomic hydrogen observations is $(5.0 \pm 0.8) \times 10^{11} M_{\odot}$ (Higdon & Wallin 2003). A disk with the inclination angle of 5° is impossible, since the dynamical mass of the central gas is almost the same with the mass of the whole galaxies. A disk with the inclination angle of 10° is still too large, since more than one tenth of the total mass is concentrated within a thousand radius of. A disk with the inclination angle of 30° can be possible. We therefore think that this face-on configuration can be possible only if the inclination angle is ~30° or larger.

The latter molecular gas configuration has an edge-on structure, so the structure should have thin disk- or ringlike structure, or it can be torus-like structure but has to have a clumpy internal structure to expose the BLR at the center. Such clumpy structure is suggested theoretically (Wada & Norman 2002), and with their model, the column density of $\sim 10^{21} \text{ cm}^{-2}$ is possible even with the inclination angle of ~60°. Under this model, the difference of the column density derived from our CO data and from the X-ray data can be explained; the spatial resolution of our observation is about 250 pc, which smears all the internal clumpy structures, and therefore the derived column density will be the average value and higher than that derived from X-ray observations, which only trace very narrow column densities due to the very small size scale of the X-ray-emitting region (< 1 pc). Under these nearly edge-on configurations, the rotational velocity is in the typical values for other galaxies (<500 km s$^{-1}$), and therefore we do not need to invoke any special conditions.

Of course, there is another possibility—that the central component is nothing related to the hypothetical torus, namely, the central component we observed is just a part of the galactic disk gas. This is supported by the similar trend and the smooth connection of the molecular gas kinematics at the nucleus and the ring. Since the infalling motion exists from the ring to the nucleus along the nuclear bar or spiral (Prieto et al. 2005; Fathi et al. 2006), it is natural to pile up the gas around the nucleus with similar kinematics as that of the ring. In this case, gas will rotate around the nucleus with similar inclination as the outer disk or the ring, and it is natural not to cover the line-of-sight toward the AGN; namely, the gas configuration will be similar to the Seyfert 1 nucleus. In addition, if the molecular gas piles up at the diameter smaller than our beam size of 200–300 pc, the discrepancy of the column density estimated from our data and the X-ray data can also be explained. Here we briefly estimate the necessary gas infall rate to create the central component with gas infall from the molecular ring. The H$_2$ masses of the central component is $6.5 \times 10^7 M_{\odot}$, so that the mass infall rate of 0.5 $M_{\odot}$ yr$^{-1}$ is required to create this component within the molecular ring gas consumption timescale of $1.2 \times 10^4$ yr (§4.1). Note that the line ratio of the central component is obviously different from that in other regions or other galaxies, and this can be explained either by the shock caused by the gas inflow along the nuclear bar or nuclear spiral, or by AGN activities, such as irradiation of strong X-ray emission to the central component.

In summary, the central component can be the circumnuclear disk or torus with nearly edge-on ($\geq 60°$) clumpy structure, or less likely nearly face-on ($\geq 30°$) disk/torus. The
central component can also be nothing related to the hypothetical disk/torus, and possibly created by the gas inflow from the molecular ring. The physical conditions of the central component are different from that of molecular gas in other regions, so that even it is not the hypothetical disk/torus, it should be highly related to the AGN activities or gas inflow toward the nucleus.

5. SUMMARY

We successfully imaged the central component and the molecular ring, which is spatially coincident with the AGN and the starburst ring, toward the central region of the Seyfert 1 galaxy NGC 1097 using the SMA in the $^{12}$CO $J = 2-1$ line. Here are the summary for the nature of the central component we observed:

1. We found that the $^{12}$CO $J = 2-1$ map shows an intensity peak at the central component, and different from the $^{12}$CO $J = 1-0$ map, which shows the intensity peak at the molecular ring.

2. The $^{12}$CO $J = 2-1$/\(^{13}$CO $J = 1-0$ line intensity ratio for the central component is $1.9 \pm 0.2$, which is different from the global values in GMCs or in spiral galaxies of about unity or less. From the LAVG analysis, we estimated that the central component is warmer ($T_K \gtrsim 400$ K) and denser ($n_H \sim 3 \times 10^8$ cm$^{-3}$) than that of the normal molecular clouds assuming a normal Z($^{12}$CO)/($d_v$/$d_r$). These values depend highly on the Z($^{12}$CO)/($d_v$/$d_r$), and lower Z($^{12}$CO)/($d_v$/$d_r$) for an order of magnitude decreases the temperature and density of about an order of magnitude. The effect of intense star formation and/or AGN activities, such as shocks induced by numerous supernova explosions or strong X-ray radiation from AGN are presumably the causes of the unusual line ratio.

3. Faster rotation feature of the central gas is observed in NGC 1097, which is similar results as observed in other Seyfert 2 galaxies. We interpret this feature as a highly inclined clumpy disk/torus or thin disk to explain the fast rotation and the difference between the column density derived from CO and X-ray observations. A low-inclined ($i \sim 30^\circ$) thick disk is possible, but lower inclination than this value is less likely since it is rare to see a velocity $\geq 500$ km s$^{-1}$ in nearby galaxies, and the total mass of central disk turns to be too large compared with the total mass of the galaxy. On the other hand, the central component can also be interpreted as just an inner extension of the galactic disk, possibly created by the gas inflow from the molecular ring.

4. Combining kinematical and spatial information with the physical conditions, we suggest that the central gas is related to the Seyfert activities or gas inflow.

Here is a summary for the nature of the molecular ring we observed: The $R_{21}$ of the molecular ring is $1.3 \pm 0.2$, which shows a similar properties to the star-forming GMCs in our Galaxy or nearby starburst galaxies. In addition, since the molecular ring shows a good spatial coincidence with the starburst ring, so we expect that the molecular ring is actually fueling the starburst activities. The molecular gas mass content with respective to the dynamical mass, on the other hand, shows somewhat low value, so that high $R_{21}$ may not be related to star formation activities, but to other activities, such as shock induced by gas inflow along the bar. Without further replenishment, it can last for only about $1.2 \times 10^8$ yr, but since there seems to have gas flows from the dust lane along the large-scale bar toward the molecular ring, and from the molecular ring toward the nucleus, this timescale is highly uncertain.

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