THE CIRCUMNUCLEAR MOLECULAR GAS IN THE SEYFERT GALAXY NGC 4945

RICHARD C. Y. CHOU
Institute of Astronomy and Astrophysics, Academia Sinica, P.O. Box 23-141, Taipei, Taiwan; and Department of Astronomy and Astrophysics, University of Toronto, 50 St. George Street, Toronto, ON M5S 3H4, Canada; chou@astro.utoronto.ca

A. B. PECK
Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138; apeek@cfa.harvard.edu

J. LIM, S. MATSUSHITA, S. MULLER, S. SAWADA-SATOH, AND DINH-V-TRUNG
Institute of Astronomy and Astrophysics, Academia Sinica, P.O. Box 23-141, Taipei, Taiwan; jlim@asiaa.sinica.edu.tw, satoki@asiaa.sinica.edu.tw, muller@asiaa.sinica.edu.tw, satoko@asiaa.sinica.edu.tw, trung@asiaa.sinica.edu.tw

F. BOONE
Observatoire de Paris, LERMA, 61, av. de l’Observatoire, F-75014 Paris, France; frederic.boone@obspm.fr

AND

C. HENKEL
Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany; p220hen@mpifr-bonn.mpg.de

Received 2007 April 16; accepted 2007 June 26

ABSTRACT

We have mapped the central region of NGC 4945 in the \( J = 2 \rightarrow 1 \) transition of \(^{12}\)CO, \(^{13}\)CO, and C\(^{18}\)O, as well as the continuum at \( \sim 1.3 \) mm, at an angular resolution of \( 5'' \times 3'' \) with the Submillimeter Array. The relative proximity of NGC 4945 (distance of only 3.8 Mpc) permits a detailed study of the circumnuclear molecular gas and dust in a galaxy exhibiting both an active galactic nucleus (AGN; classified as Seyfert 2) and a circumnuclear starburst in an inclined ring with radius \( \sim 2.5'' \) (\( \sim 50 \) pc). We infer the systemic velocity \( \sim 585 \) km s\(^{-1}\) from channel maps and PV-diagrams. We find that all three molecular lines trace an inclined rotating disk with the major axis aligned with that of the starburst ring and large-scale galactic disk and which exhibits solid-body rotation within a radius of \( \sim 5'' \) (\( \sim 95 \) pc). The rotation curve flattens beyond this radius, and the isovelocity contours exhibit an S-shaped asymmetry suggestive of a highly inclined bar, as has been invoked to produce a similar asymmetry observed on larger scales. We infer an inclination for the nuclear disk of \( 62^\circ \pm 2^\circ \), somewhat smaller than the inclination of the large-scale galactic disk of \( \sim 78^\circ \). The continuum emission at 1.3 mm also extends beyond the starburst ring and is dominated by thermal emission from dust. If it traces the same dust emitting in the far-infrared, then the bulk of this dust must be heated by star-formation activity rather than the AGN. We discover a kinematically decoupled component at the center of the disk with a radius smaller than 1.4'' (27 pc), which spans approximately the same range of velocities as the surrounding disk. This component has a higher density than its surroundings and is a promising candidate for the circumnuclear molecular torus invoked by AGN unification models.

Subject headings: galaxies: active — galaxies: individual (NGC 4945) — galaxies: Seyfert — galaxies: starburst — intergalactic medium — radio lines: galaxies

Online material: color figures

1. INTRODUCTION

NGC 4945 is a nearby, almost edge-on (\( i = 78^\circ \)), disk galaxy [type SB(s)cd or SAB(s)cd] that is a member of the Centaurus Group of galaxies (Webster et al. 1979). Its distance, determined most accurately from the luminosity of stars at the tip of the red giant branch, is \( 3.82 \pm 0.31 \) Mpc (Karachentsev et al. 2007). This value is consistent with previous more crude estimates of the distance to NGC 4945 (see the discussion in Bergman et al. 1992), and so we hereafter assume that \( i = 90^\circ \) corresponds to 19 pc in NGC 4945.

The central region of NGC 4945 contains an active galactic nucleus (AGN) revealed most unambiguously by its strong and variable hard X-ray emission (Iwasawa et al. 1993; Done et al. 1996; Madejski et al. 2000). H\(_2\)O megamaser emission has been detected from the nucleus, likely distributed in a disk with radius of \( \sim 15 \) mas (\( \sim 0.3 \) pc) around the AGN (Greenhill et al. 1997). The AGN is classified as Seyfert 2 (Braatz et al. 1997; Madejski et al. 2000; Schurch et al. 2002), consistent with findings that Seyfert 2 but not Seyfert 1 galaxies exhibit water megamasers (e.g., review by Lo 2005). Surrounding the AGN, there is an inclined circumnuclear starburst ring with a radius of \( \sim 2.5'' \) (\( \sim 50 \) pc) seen most clearly in Pa\(_{\alpha}\) (Marconi et al. 2000). The central region of NGC 4945 is among the strongest and most prolific extragalactic sources of molecular lines (e.g., Henkel et al. 1994; Curran et al. 2001; Wang et al. 2004). For these reasons, NGC 4945 is a particularly attractive candidate for studying the nature of molecular gas at the center of an active galaxy and the role this gas plays in fueling and perhaps also determining in part the observed properties of both the circumnuclear starburst and AGN.

Because of its southerly declination (\( \delta = -49^\circ \)), studies of the molecular gas in NGC 4945 have been largely restricted to single-dish telescopes, in particular the 15 m Swedish-ESO Submillimeter Telescope (SEST). Whiteoak et al. (1990) made the first map of the central region of this galaxy in the \( J = 1 \rightarrow 0 \) transition of \(^{12}\)CO, \(^{13}\)CO, and C\(^{18}\)O at an angular resolution of \( 3'' \times 3'' \).
transition of $^{12}$CO at an angular resolution of $43''$ (measured at full width at half-maximum [FWHM], used hereafter when quoting sizes). They attributed the observed strong central concentration of molecular gas to a disk with a radius of $\sim 18''$ (340 pc). With just a single pointing at the nucleus, Bergman et al. (1992) obtained high-quality spectra of both $^{12}$CO and $^{13}$CO in the $J = 1 \rightarrow 0$ transition. They found that the observed line ratio as a function of velocity can be modeled as a homogenous ring in rigid-body rotation with an inner radius of $\approx 8''$ ($\approx 150$ pc) and an outer radius of $\approx 15''$ ($\approx 280$ pc).

Dahlem et al. (1993) mapped the central region of NGC 4945 in both the $J = 1 \rightarrow 0$ and $2 \rightarrow 1$ transitions of $^{12}$CO at an angular resolution of $43''$ and $24''$, respectively. Based on the measured position-velocity diagram along the major axis of NGC 4945 in both transitions, they inferred the presence of a ring with a radius of $8'' \pm 3''$ ($\approx 150$ pc) in the $J = 2 \rightarrow 1$ and $15'' \pm 3''$ ($\approx 280$ pc) in the $J = 1 \rightarrow 0$ transitions. They noted that this did not necessarily suggest the presence of two rings, but rather a radial variation in the excitation conditions and/or optical depth in a single ring with a given radial thickness.

Mauersberger et al. (1996) mapped the central region of NGC 4945 in the $J = 3 \rightarrow 2$ transition of $^{12}$CO at an angular resolution of $15''$. In this transition, they found an intrinsic size for the central concentration of radius $5.2'' \pm 1.5''$ ($\approx 100$ pc) along its major axis. Although the position-velocity diagram is once again consistent with a ring but with an even smaller radius than in lower $^{12}$CO transitions, Mauersberger et al. (1996) were careful to point out that other structures (e.g., disk, bar, spiral, or even two independent molecular concentrations) are possible.

All the above-mentioned single-dish observations infer the presence of a molecular ring with size smaller than the respective angular resolutions of these observations. It is not clear how this molecular ring is related to the starburst ring, whether it comprises the reservoir for fueling the active nucleus, and whether it is related to the hypothetical circumnuclear molecular torus required by AGN unification models (Antonucci 1993). Observations at higher angular resolutions are needed to spatially resolve and hence clarify the spatial-kinematic distribution of the molecular gas at the center of NGC 4945. The first such observations were made quite recently by Cunningham & Whiteoak (2005), who used the Australia Telescope Compact Array (ATCA) to map a central region of radius $17''$ (323 pc) in the $J = 1 \rightarrow 0$ transitions of HCN, HCO$^+$, and HNC at an angular resolution of $5.6'' \times 3.5''$ (106 $\times$ 66 pc). These lines trace molecular gas at about an order of magnitude higher density ($\sim 10^4$–$10^5$ cm$^{-3}$) than the above-mentioned $^{12}$CO lines ($\sim 10^3$–$10^4$ cm$^{-3}$). The HNC map, which best traces the overall spatial-kinematic distribution of the molecular gas, reveals an inclined rotating disk-like feature with a radius of $4.25'' \pm 0.25''$ ($\approx 80$ pc) along the major axis and position angle (PA) of $64^\circ$, somewhat misaligned from the major axis of both the starburst ring and large-scale galactic disk at a PA of $\approx 45^\circ$. Based on the measured position-velocity diagram, Cunningham & Whiteoak (2005) argue that the HNC line traces a ring with an inner radius of $3''$ (57 pc). Their maps, however, are affected by a lack of short baselines that result in an inability to detect structures larger than $\sim 15''$ ($\approx 285$ pc). Furthermore, line absorption against the strong central molecular source at their observing wavelength of 3.3 mm (90 GHz) may compromise the detectability of the innermost features.

Here, we present the first interferometric observations of the central region of NGC 4945 in $^{12}$CO as well as in $^{13}$CO and C$^{18}$O at their $J = 2 \rightarrow 1$ transitions. The angular resolution attained is much higher than previous single-dish CO observations, and we properly resolve for the first time the central molecular gas concentration in CO lines. Our maps recover virtually all the emission detected in single-dish observations and are not affected by line absorption against the central continuum source. We show that the CO gas is distributed in an inclined disk exhibiting rigid-body rotation out to a radius of $\approx 5''$ ($\approx 95$ pc); i.e., the molecular disk extends beyond the circumnuclear starburst ring seen in Pa$\alpha$. The rotation curve flattens beyond this radius, and the isovelocity contours exhibit an S-shaped asymmetry suggestive of a highly inclined bar as has been invoked to produce a similar asymmetry in both molecular and atomic hydrogen gas extending to much larger radii.

We do not detect any central hole in the disk, placing an upper limit of $\approx 2.2''$ (42 pc) on the radius of any such hole. Instead, we detect for the first time a spatially unresolved component at the center of the disk that is kinematically decoupled from the surrounding disk. This inner component exhibits a broad velocity width comparable with the overall range in velocities exhibited by the surrounding disk and is a good candidate for the hypothesized circumnuclear molecular torus invoked by AGN unification models (Antonucci 1993).
was scaled from observations of Callisto. The quasar 3C 279 was observed for bandpass calibration.

We calibrated the data in the standard fashion using the software package MIRIDL, and made images using AIPS. The results shown in this paper correspond to the data taken on May 24 only. Data taken on May 22, at a different sidereal time, have a different \( \nu \) -coverage (greater number of projected baselines) and deep negative sidelobes that made imaging of the line emission difficult. To make a map of the continuum emission, we used the line-free channels (total bandwidth of 3 GHz) in both the LSB and USB. To make maps in line emission, we first used the line-free channels in the visibility plane to derive the continuum emission, which was then subtracted from all the channels. The synthesized beam achieved with natural weighting of the visibilities is \( 5.1'' \times 2.8'' \) (\( \sim 100 \times 50 \) pc) at a PA of 8.8°.

### 3. RESULTS AND INTERPRETATION

#### 3.1. Continuum Emission

##### 3.1.1. Contribution from Dust

In Figure 1 we show a map of the 1.3 mm continuum emission superposed on a \( \text{Pa}_\alpha \) image of the central region of NGC 4945 taken from Marconi et al. (2000). The continuum source has a total flux density of 1.3 ± 0.2 Jy and is clearly resolved. Gaussian fitting yields a deconvolved size (at FWHM) of \( 9.8'' \times 5.0'' \) (\( \sim 0.3'' \)) (186 × 95 pc) with the major axis at a PA of 28° ± 3°. The centroid of this source is located at \( \alpha (2000.0) = 13^h 05^m 27.59'' \pm 0.01'' \) and \( \delta (2000.0) = -49^\circ 28' 06.1'' \pm 0.2'' \), which is 1.8° to the southeast of the nominal centroid of the \( \text{H}_2 \text{O} \) masergas (Greenhill et al. 1997). The latter coincides within measurement uncertainties with the centroid of the central radio continuum source detected at centimeter wavelengths (Elmouttie et al. 1997) and presumably marks the location of the AGN.

The major axis of the 1.3 mm continuum source is not aligned with the major axis of either the starburst ring or larger scale galactic disk, both of which have PA ≈ 45°. Along the major axis of the \( \text{Pa}_\alpha \) starburst ring, the 1.3 mm continuum extends beyond the inner bright rim of the starburst ring at a radius of \( \sim 2.5'' \) (\( \sim 50 \) pc) and also beyond the detectable outer radius of this ring at \( \sim 5'' \) (\( \sim 100 \) pc). On the southeastern side of the ring, the 1.3 mm continuum clearly extends beyond the measured extent of the \( \text{Pa}_\alpha \) emission.

The central region of NGC 4945 has been imaged in the continuum at centimeter wavelengths at angular resolutions comparable with that attained here. At 21 cm (1.4 GHz), the source has a deconvolved size of \( 7.6'' \times 3.4'' \) (\( \pm 0.2'' \)) with the major axis at PA = 42.5° and a total flux density of 4.6 ± 0.1 Jy (Ott et al. 2001). At 5 cm (6 GHz), the source has a smaller deconvolved size of \( 5.7'' \times 2.0'' \) (\( \pm 0.1'' \)) at PA = 43° ± 1° and a total flux density of 2.04 ± 0.04 Jy (Whiteoak & Wilson 1990). The size of the continuum source at centimeter wavelengths is therefore much smaller than that measured at 1.3 mm. Instead, the centimeter continuum source has a size comparable with the starburst ring, and its major axis is aligned with that of the starburst ring. The steep negative spectral index of this source indicates that nonthermal (synchrotron) emission dominates at centimeter wavelengths and presumably arises from star formation–related activity (e.g., supernovae) in the starburst ring (in addition to any unresolved emission from the AGN).

Cunningham & Whiteoak (2005) have imaged the central continuum source at 3.3 mm (90 GHz) at an angular resolution comparable with that attained here. Like us, they find an elongated source whose centroid is offset to the southeast of the \( \text{H}_2 \text{O} \) megamasers, and whose major axis is at PA ≈ 29°. With a reported deconvolved source size of 7.6'' × 2.0'' and peak flux density of 0.13 Jy, the corresponding total flux density for a Gaussian source is \( \sim 1.0 \) Jy. Extrapolating from 21 cm and 5 cm, the expected flux density at 3.5 mm is \( \sim 0.5 \) Jy, only one-half of that actually measured. Extrapolating to 1.3 mm, the estimated contribution from nonthermal emission is \( \sim 0.3 \) Jy, less than one-quarter of the flux density measured at this wavelength. Even if we assume that nonthermal emission dominates at 3.3 mm, this emission would only contribute at most about one-half of the total flux density measured at 1.3 mm. Thus, we conclude that dust emission dominates at 1.3 mm (and also contributes significantly at 3.3 mm) and that this explains the different dimensions and PAs of the source at millimeter and centimeter wavelengths. In § 4.1 we discuss the implications of these results for the origin of the central far-IR emission from NGC 4945.

##### 3.1.2. Molecular Gas Mass from Dust

To estimate the mass of molecular gas from the inferred dust emission at 1.3 mm (assuming a gas-to-dust ratio of 100), we first subtract the estimated contribution from nonthermal emission (\( \sim 0.3 \) Jy) from the total continuum emission (\( \sim 1.3 \) Jy). The gas mass is then given by (Hildebrand 1983)

\[
M_{\text{gas}}(M_\odot) = 1.73 \times 10^3 \frac{S_\nu [\text{mJy}]}{D^2} \frac{\lambda^{2} [\text{mm}]}{T_D [K]} \frac{\kappa_a(\nu)[g^{-1} \text{cm}^2]}{},
\]

where the dust continuum flux density \( S_\nu \approx 1 \) Jy, distance \( D = 3.82 \) Mpc, wavelength \( \lambda = 1.3 \) mm, and dust absorption coefficient \( \kappa_a(1.3 \text{ mm}) \approx 3 \times 10^{-3} \text{ g}^{-1} \text{ cm}^2 \). Assuming a dust temperature \( T_D \approx 40 \) K, as inferred from far-IR measurements (Brock et al. 1988), we find that \( M_{\text{gas}} \approx 3.6 \times 10^8 M_\odot \). If we adopt a dust temperature corresponding to the peak brightness temperature measured in \( ^{12}\text{CO}\text{(2}}-1) \) of \( \sim 30 \) K (§ 3.2), the gas mass is then \( M_{\text{gas}} \approx 4.7 \times 10^8 M_\odot \). As we shall show in § 3.2.3,
the gas mass inferred from dust is comparable with values inferred from the three observed CO lines.

3.2. Line Emission

3.2.1. Spatial-Kinematic Structure

Like the continuum emission, the \(^{12}\)CO(2–1), \(^{13}\)CO(2–1), and \(^{13}\)CO\(^{18}\)O(2–1) lines are strongly concentrated toward the center of NGC 4945. Figures 2 and 3 respectively show channel maps of the \(^{12}\)CO(2–1) and \(^{13}\)CO(2–1) emission smoothed to a velocity resolution of \(\sim 20\) km s\(^{-1}\), with the circumnuclear starburst ring seen in Pa\(\alpha\) plotted as an ellipse. In Figure 4 we show the corresponding total intensity (moment 0) as well as intensity-weighted mean-velocity (moment 1) maps.

An inspection of these maps reveals that the molecular emission originates (primarily) from a highly inclined rotating disk extending beyond the Pa\(\alpha\) starburst ring. Gaussian fitting to the moment maps yields a deconvolved size (at FWHM) for the disk of 16.4'' \(\pm\) 10.8'' \(\pm\) 0.1'' \(\sim 310 \times 205\) pc and major axis at PA = 38° \(\pm\) 1° in \(^{12}\)CO(2–1), a size of 14.2'' \(\pm\) 6.6'' \(\pm\) 0.1'' \(\sim 270 \times 125\) pc and PA = 43° \(\pm\) 1° in \(^{13}\)CO(2–1), and a size of 13.1'' \(\times\) 4.7'' \(\pm\) 0.1'' \(\sim 250 \times 90\) pc and PA = 45° \(\pm\) 1° in \(^{13}\)CO\(^{18}\)O(2–1). The derived PA of the major axis in the more optically thin \(^{13}\)CO(2–1) and \(^{13}\)CO\(^{18}\)O(2–1) lines is in good agreement with the PA along which the velocity gradient of the disk reaches a maximum in these lines. The major axis of the disk (mean PA = 44°) is therefore well aligned with that of the starburst ring as well as the larger scale galactic disk at a PA of \(\sim 45\)°. We see no evidence for the central hole in our data, suggesting that any central hole in this disk has a size smaller than the synthesized beam, which measures 4.4'' along the major axis of the disk.

In all three molecular lines, the inner region of the disk within a radius of \(\sim 5''\) \(\sim 95\) pc appears to exhibit simple circular rotation with the isovelocity contours perpendicular to the major axis of the disk, as can be seen in Figure 4. Beyond this radius, however, the disk exhibits significant deviations from circular rotation as can be best seen in \(^{12}\)CO(2–1). Here, the isovelocity contours on the northeastern side of the disk twist to the north, and on the southwestern side twist to the south, producing an S-shaped asymmetry. In this outer region, the spatial structure of the disk closely resembles the distribution of the 1.3 mm continuum emission (e.g., the southeast extension), reinforcing our earlier argument that the continuum emission at 1.3 mm is likely dominated by dust.

The position-velocity (PV) diagrams of all three molecular lines along the inferred major axis of the disk are shown in Figure 5. The PV-diagrams along the major axis in \(^{13}\)CO(2–1) and \(^{13}\)CO\(^{18}\)O(2–1) indicate (primarily) rigid-body rotation, while in \(^{12}\)CO(2–1) it shows additional complex emission with a broad velocity width at or near disk center. Cuts along different PAs reveal that this “excess” emission is always present as a (vertical) strip in velocity at the origin of the PV-diagram, not just in \(^{12}\)CO(2–1), but also in \(^{13}\)CO(2–1) and \(^{13}\)CO\(^{18}\)O(2–1). For example, in Figure 5 we also show the PV-diagrams along the minor axis of the disk (PA = 134°), as well as halfway between the major and minor axes of the disk (PA = 89°), in all three molecular lines. Armed with this knowledge, a closer inspection reveals that this feature can just be seen in the PV-diagrams along the minor axis of the disk in \(^{13}\)CO(2–1) and \(^{13}\)CO\(^{18}\)O(2–1). This feature
therefore corresponds to a kinematically decoupled component with a size smaller than the synthesized beam (i.e., projected radius as small as 1.4" or 27 pc) located at the center of the disk. In the channel maps, this kinematically decoupled feature appears as the ever-present emission toward the center of the disk even at the most blueshifted and redshifted velocities detectable. By contrast, in an inclined disk exhibiting only rigid-body rotation, the most blueshifted and redshifted velocities should originate from just the outermost regions of the disk along its major axis.

We infer from both the channel maps and PV-diagrams a systemic velocity of \( \sim 585 \text{ km s}^{-1} \) measured with respect to the local standard of rest. (All velocities quoted here are relative to the local standard of rest, which is 4.6 km s\(^{-1}\) lower than the heliocentric velocity.) By contrast, single-dish observations in \(^{12}\text{CO}(1-0)\) and \(^{12}\text{CO}(2-1)\) infer a significantly lower systemic velocity of \( \sim 558 \text{ km s}^{-1} \) (Whiteoak et al. 1990; Bergman et al. 1992; Dahlem et al. 1993). The HNC observation of Cunningham & Whiteoak (2005) indicates a systemic velocity, as measured at the midpoint between the two strongest HNC peaks in the PV-diagram (their Fig. 11), of \( \sim 570 \text{ km s}^{-1} \), about halfway between single-dish and our interferometric CO measurements.

The systemic velocity inferred from interferometric observations in atomic hydrogen (H\(^1\) gas (Ott et al. 2001), averaged over the entire galaxy, is \( 557 \pm 3 \text{ km s}^{-1} \), in agreement with the above-mentioned value derived from single-dish CO measurements. On the other hand, H\(^1\) detected in absorption toward the centroid of the central continuum source has a velocity of \( \sim 585 \text{ km s}^{-1} \) (see Fig. 5 of Ott et al. 2001), similar to the systemic velocity inferred here. Arcsecond imaging of hydrogen recombination lines near 8.6 GHz (Roy et al. 2005) shows that the emission peaks at the location of the central radio continuum source; these recombination lines have a systemic velocity of \( \sim 576 \text{ km s}^{-1} \), again close to that inferred here. We therefore conclude, based on observations that better trace gas closer to the center of the galaxy, that the systemic velocity of NGC 4945 is more likely about 585 km s\(^{-1}\).

3.2.2. Comparison with Single-Dish Observations

The \(^{12}\text{CO}(2-1)\) emission toward the center of NGC 4945 has been observed a number of times with the SExtractor (Dahlem et al. 1993; Henkel et al. 1994; Curran et al. 2001; Wang et al. 2004). These observations often give different line profiles and intensities, caused most likely by inaccuracies in telescope pointing. Only the \(^{12}\text{CO}(2-1)\) line profiles measured by Dahlem et al. (1993) and Henkel et al. (1994) appear similar and also agree with that measured here. In Figure 6 we plot our spatially integrated \(^{12}\text{CO}(2-1)\) line profile corrected for the primary beam of the SMA and convolved to the primary beam of SExtractor, together with the line profile measured by Henkel et al. (1994). The integrated line intensity (in main-beam brightness temperature) we measure of \( 925 \pm 13 \text{ K km s}^{-1} \) is \( \sim 90\% \) of that measured by Henkel et al. (1994) of \( 1050 \pm 6 \text{ K km s}^{-1} \) (as quoted in Wang et al. 2004). The quoted uncertainties do not take into account any errors in flux calibration, and so we have likely recovered the bulk if not all of the \(^{12}\text{CO}(2-1)\) emission present in the same region.

The \(^{12}\text{CO}(2-1)\) and \(^{13}\text{CO}(2-1)\) emissions toward the center of NGC 4945 also have been observed a number of times with the SExtractor (Henkel et al. 1994; Curran et al. 2001; Wang et al. 2004). The \(^{13}\text{CO}(2-1)\) line profile we measure is similar in shape to that measured in \(^{12}\text{CO}(2-1)\), as shown in Figure 6, and
also similar to the 13CO(2–1) line profiles measured by Henkel et al. (1994) and Wang et al. (2004) but not Curran et al. (2001). The integrated line intensity we measure of 82 ± 3 K km s\(^{-1}\) is similar to that measured by Wang et al. (2004) of 81.2 ± 0.7 K km s\(^{-1}\) (which has a higher signal-to-noise ratio [S/N] than that measured by Henkel et al. 1994).

The C\(^{18}\)O(2–1) line profile we measure is again similar in shape to that measured in 12CO(2–1), but is different to those measured by either Curran et al. (2001) or Wang et al. (2004). The line profile we measure is closest in shape to that measured by Henkel et al. (1994). The integrated line intensity we measure of 31 ± 3 K km s\(^{-1}\) is also similar to that measured by Henkel et al. (1994) of 32 ± 2 K km s\(^{-1}\). In Table 1, we summarize the integrated intensities that we measure for all three lines together with the values measured by Henkel et al. (1994), Curran et al. (2001), and Wang et al. (2004) with the SEST.

3.2.3. Molecular Gas Mass from CO Lines

To estimate the mass of molecular gas traced in 12CO(2–1), we first use the conversion factor between the brightness temperature of the 12CO(1–0) line and molecular hydrogen column density of 1 × 10\(^{20}\) K\(^{-1}\) km\(^{-1}\) s cm\(^{-2}\) as has been proposed to be appropriate in the central regions of galaxies (e.g., see Paglione et al. 2001). Table 1 lists the brightness temperature of the 12CO(2–1) line if its emission as mapped with the SMA had been observed by SEST (details in § 3.2.2). In Table 2 we list the actual measured brightness of the three observed lines. Assuming a line ratio (in main-beam brightness temperature) of 12CO(2–1) to 12CO(1–0) of 1.2 ± 0.1 (from Dahlem et al. [1993] after correcting for the different beam sizes), we derive a molecular hydrogen column density of 5 ± 0.1 × 10\(^{22}\) cm\(^{-2}\). Given the measured source size as described in § 3.2.1 and listed also in Table 2, the corresponding mass in molecular hydrogen gas is therefore (1.63 ± 0.03) × 10\(^{8}\) \(M_\odot\).

To compute the molecular gas mass from the 13CO(2–1) and C\(^{18}\)O(2–1) lines, we assume that this gas is in local thermal equilibrium (LTE). We adopt the abundance ratio [12CO]/[13CO] = 50 and [12CO]/[C\(^{18}\)O] = 200 as estimated by Curran et al. (2001) and Wang et al. (2004). We assume an excitation temperature of ~30 K based on the peak brightness temperature measured for the 12CO(2–1) line (i.e., 16.5 Jy beam\(^{-1}\)) and that the 13CO(2–1) and C\(^{18}\)O(2–1) lines are optically thin. In this way, we derive a column density from the 13CO(2–1) line of (6.7 ± 0.3) × 10\(^{22}\) cm\(^{-2}\) and from the C\(^{18}\)O(2–1) line of (1.65 ± 0.17) × 10\(^{23}\) cm\(^{-2}\). Their corresponding molecular hydrogen gas masses are (1.03 ± 0.05) × 10\(^{8}\) \(M_\odot\), as traced in 13CO(2–1),
Fig. 5.—Top, left to right: Position-velocity diagram in \(^{12}\text{CO}(1-0), ^{13}\text{CO}(2-1), \) and \(^{13}\text{C}^{18}\text{O}(2-1)\) along the major axis of the disk (PA = 44°). Middle, left to right: Same as top, but with a PA halfway between the major and minor axis of the disk (PA = 89°). Bottom, left to right: Same as top, but along the minor axis of the disk (PA = 134°). In all panels, contour levels for \(^{12}\text{CO}\) are plotted from 7 σ in steps of 7 σ and contour levels for \(^{13}\text{CO}\) and \(^{13}\text{C}^{18}\text{O}\) from 3 σ in steps of 3 σ. All velocities quoted here are relative to the local standard of rest, which is 4.6 km s\(^{-1}\) lower than the heliocentric velocity. [See the electronic edition of the Journal for a color version of this figure.]
and \((1.21 \pm 0.1) \times 10^8 \, M_\odot\), as traced in \(^{15}\)O(2–1). The estimated masses in molecular gas from all three lines agree with one another and are also roughly comparable to the gas mass estimated from the dust continuum emission of \(~4.7 \times 10^8 \, M_\odot\) ([3.1.2]).

We also compute the approximate mass in molecular hydrogen gas within the region where the disk exhibits circular rotation (i.e., radius \(\leq 5^{\prime}\)). Table 3 lists the measured brightness temperature within a Gaussian region of size \(10'' \times 10''\) and PA of \(44^\circ\) centered on the disk. The inferred column density and corresponding mass in molecular hydrogen gas are \(~10^{23} \text{ cm}^{-2}\) and \(~10^7 \, M_\odot\), as listed in Table 3. We follow the same method mentioned above, and set the emitting area as \(10'' \times 4.7''\) (asume the inclination of the disk is \(62^\circ\)) to calculate the gas mass. The mass derived from \(^{12}\)CO is \((3.22 \pm 0.06) \times 10^7 \, M_\odot\), and the gas mass derived from \(^{13}\)CO and \(^{18}\)O is \((3.0 \pm 0.1) \times 10^7\) and \((3.1 \pm 0.5) \times 10^7 \, M_\odot\), respectively.

### 3.2.4. Density and Temperature

To search for any radial variations in density and temperature of the molecular gas, we computed line ratios (in measured brightness temperature) in \(^{12}\)CO/\(^{13}\)CO, \(^{12}\)CO/\(^{18}\)O, and \(^{13}\)CO/\(^{18}\)O along the major axis of the disk. The results are shown in Figure 7. Both the \(^{12}\)CO/\(^{13}\)CO and \(^{12}\)CO/\(^{18}\)O line ratios increase from the northeastern (redshifted) side to the southwestern (blueshifted) side of the disk, spanning the range \(5–15\) in \(^{12}\)CO/\(^{13}\)CO and \(13–30\) in \(^{12}\)CO/\(^{18}\)O. On the other hand, the \(^{13}\)CO/\(^{18}\)O ratio remains roughly constant along the major axis of the disk, occupying a relatively narrow range between 2.2 and 3.0.

To determine the line ratios of the inner spatially unresolved but kinematically decoupled component described in § 3.2.1, we turn to the PV-diagram along the minor axis of the disk as shown in Figure 8. Notice that the emission from this inner component away from the velocity range \(520–650 \, \text{km s}^{-1}\), which straddles the systemic velocity, can be well separated from that of the surrounding disk. In this way, we compute for the inner component line ratios that span the range \(12–17\) in \(^{12}\)CO/\(^{13}\)CO, \(17–26\) in \(^{12}\)CO/\(^{18}\)O, and \(1.2–1.5\) in \(^{12}\)CO/\(^{18}\)O. By comparison, the corresponding line ratios along the minor axis at velocities in the range \(520–650 \, \text{km s}^{-1}\), where emission from the inner component and surrounding disk cannot be easily separated, are generally lower, spanning the range \(8–15\) for \(^{12}\)CO/\(^{13}\)CO, \(14–18\) for \(^{12}\)CO/\(^{18}\)O, and \(1.2–1.6\) for \(^{13}\)CO/\(^{18}\)O.

We have used the LVG approximation (Goldreich & Kwan 1974) to compute the physical conditions of the molecular gas implied by the measured line ratios. The collision rates for CO in the temperature range \(10–250 \, \text{K}\) were taken from Flower & Launay (1985) and \(500–2000 \, \text{K}\) from McKee et al. (1982). In these calculations, we adopted a relative abundance of \(^{13}\)CO/\(^{12}\)CO = \(4 \times 10^{-6}\) (Solomon et al. 1979) and isotopic ratios \((^{12}\text{CO})/(^{13}\text{CO}) = 50\) and \((^{12}\text{CO})/(^{18}\text{O}) = 200\) (Wang et al. 2004). We assume that the emission in all lines are emitted from the same region (i.e., a one-zone model) and assume a velocity gradient \(dv/dr = 1 \, \text{km s}^{-1} \, \text{pc}^{-1}\), given the measured line width and diameter for the \(^{13}\)CO-emitting region of \(~285 \, \text{km s}^{-1}\) and \(~270 \, \text{pc}\), respectively. The results for all three sets of line ratios are shown together in Figure 9 and exhibit the following trends: (1) at temperatures \(T \lesssim 100 \, \text{K}\), all three line ratios exhibit only a weak dependence on temperature, with lower ratios corresponsing to higher densities; (2) at temperatures \(T > 100 \, \text{K}\), for a given line ratio the density increases with temperature, with smaller line ratios continuing to indicate higher densities; and (3) the line ratios \(^{12}\)CO/\(^{18}\)O and \(^{13}\)CO/\(^{18}\)O tend to indicate a higher density than \(^{12}\)CO/\(^{13}\)CO.

The measured line ratios therefore imply a decrease in gas density and column density from the northeastern (redshifted) side to the southwestern (blueshifted) side of the disk. Our measurements do not place strong constraints on the gas temperature, but we note that the measured \(^{12}\)CO/\(^{13}\)CO line ratios are comparable to average values of \(~13 \pm 5\) found in starburst galaxies (Aalto et al. 1995) and \(~13 \pm 1\) in Seyfert galaxies (Papadopoulos & Seaquist 1998). If the similar line ratios indicate similar physical conditions, then the preferred solution is for temperatures \(T < 100 \, \text{K}\) and densities \(n(H_2) \approx 10^3 \, \text{cm}^{-3}\), typical values of the bulk properties for giant molecular clouds in our Galaxy. In this regime, the gas density changes by a factor of just a few across the major axis of the disk. Consistent with this idea, single-dish observations in multiple lines and transitions find a density of \(~3–5) \times 10^3 \, \text{cm}^{-3}\) and temperature of \(~100 \, \text{K}\) (Henkel et al. 1994; Curran et al. 2001; Wang et al. 2004) for the bulk of
the centrally unresolved molecular gas. At radii beyond \(\sim 10''\) (\(\sim 190\) pc) at or beyond the outer regions of the disk, where 13CO and C\(^{18}\)O are not detectable at our sensitivity limits, the line ratios 12CO/13CO and 12CO/C\(^{18}\)O have lower limits that are larger than their measured values at smaller radii. This indicates that the outer region of the disk is dominated by relatively diffuse gas at densities of \(\sim 10^2\) cm\(^{-3}\).

The inner kinematically decoupled component exhibits a 13CO/C\(^{18}\)O line ratio that is near unity (1.2–1.5); i.e., the less opaque C\(^{18}\)O line has nearly the same flux density as the 13CO line. The 12CO/C\(^{18}\)O line ratio of 14–18 also is relatively low compared with values in the range 40–70 typically found in other galaxies (see Sage et al. 1991; Henkel & Mauersberger 1993). At face value, this suggests that even the 13CO and C\(^{18}\)O lines are nearly optically thick in the inner kinematically decoupled component. Alternatively, the C\(^{18}\)O species may be unusually abundant within the inner component.

We consider the second possibility first. \(^{18}\)O enrichment can occur through its production from \(^{16}\)N by He-burning in high-mass stars (\(\sim 8\, M_\odot\)) and subsequently be dispersed in the Wolf-Rayet phase or in Type II supernova explosions (Sage et al. 1991; Henkel & Mauersberger 1993; Amari et al. 1995). Such enrichment may have occurred during past circumnuclear starburst activity in NGC 4945, analogous to that currently seen as the Pa\(_c\) ring. Such low line ratios are seen in at least one other star-forming galaxy, NGC 6946 (Meier & Turner 2004). On the other hand, not all star-forming galaxies show such low line ratios; e.g., both M82 (Weiss et al. 2001) and NGC 253 (Sakamoto et al. 2006) exhibit 12CO/C\(^{18}\)O or 13CO/C\(^{18}\)O line ratios comparable with means observed in other galaxies.

We turn back to the first possibility, which requires both the 13CO and C\(^{18}\)O lines to be optically thick. To infer the required physical properties of the molecular gas, we use the same LVG approximation and the same assumptions as before for the surrounding disk, except that we now assume an order of magnitude higher velocity gradient, as is more appropriate for the inner component. The results are shown in Figure 10, which reveals that the physical properties of the gas derived from the 12CO/13CO and 12CO/C\(^{18}\)O line ratios are comparable but very different from those derived from the 13CO/C\(^{18}\)O line ratio. Our results imply that the one-zone model is not valid for the inner kinematically decoupled component, and that the 13CO(2–1) and C\(^{18}\)O(2–1) lines trace a different denser region than the 12CO(2–1) line. This situation is not uncommon in galaxies, with the 12CO emission originating from more extended and diffuse gas and the 13CO or C\(^{18}\)O emission from more compact and dense gas (e.g., Downes et al. 1992; Wall et al. 1993; Aalto et al. 1995). The physical properties of the molecular gas as inferred from the 12CO/13CO and 12CO/C\(^{18}\)O line ratios are comparable with those inferred in the surrounding disk, and presumably correspond to the more diffuse part of the inner component. On the other hand, the measured 13CO/C\(^{18}\)O line ratio implies that even at temperatures as low as \(T \approx 10\, K\), the gas density is \(\lesssim 5 \times 10^2\) cm\(^{-3}\). This is 1–2 orders of magnitude higher than the gas density in the surrounding disk and presumably corresponds to the denser part of the inner component. The inferred gas density of the denser part of the disk increases toward higher temperatures, with densities about an order of magnitude higher still at \(T \approx 100\, K\).

### 4. DISCUSSION

#### 4.1. Dust Heating

NGC 4945 is one of the three brightest IRAS point sources beyond the Magellanic clouds. It has a far-IR luminosity of \(\sim 2 \times 10^{10}\, L_\odot\) (Brock et al. 1988), which is comparable with that radiated at all other wavelengths combined. Nearly all (at least 80%) of the far-IR emission arises from a central region no larger than \(12'' \times 9''\) (230 pc \(\times\) 170 pc), which is comparable in size to the central continuum source that we detected at 1.3 mm. The far-IR emission from this central source is attributed to dust at a temperature of \(\sim 40\, K\).

As pointed out by Marconi et al. (2000), it is not clear whether the central dust-emitting region in NGC 4945 is heated by the AGN or circumnuclear starburst. This situation reflects the general difficulty in deducing the nature of the source that heats dust in the nuclear region of active galaxies. In the case of NGC 4945, our observation reveals that the central dust that emits at 1.3 mm (size \(\sim 190\) pc along the major axis) spans the entire observable extent and somewhat beyond the circumnuclear starburst ring. This spatially extended dust is unlikely to be heated predominantly by the AGN, as the latter is embedded in obscuring material that prevents UV photons (13.6 eV \(< \nu < 500\) eV) from penetrating beyond a distance of at most 1.5\(''\) (30 pc) from the center (Marconi et al., 2000). Even soft X-rays from the AGN can only escape along a X-ray plume (believed to be blown by a nuclear starburst) that emerges northwest of center (Schurch et al. 2002); i.e., the axis of the X-ray plume is orthogonal to the plane.

| Line | Total Flux (Jy) | \(\int T_{\text{mb}}\, dv\) (K km s\(^{-1}\)) | Column Density \((10^{22}\, \text{cm}^{-2})\) | Hydrogen Gas Mass \((10^7\, M_\odot)\) |
|------|----------------|---------------------------------|---------------------------------|-------------------------------|
| 12CO | 251 \(\pm\) 5 | 2478 \(\pm\) 49 | 2.07 \(\pm\) 0.04 | 3.22 \(\pm\) 0.06 |
| 13CO | 29 \(\pm\) 1  | 323 \(\pm\) 15 | 1.94 \(\pm\) 0.09 | 3.0 \(\pm\) 0.1  |
| C\(^{18}\)O | 11 \(\pm\) 1 | 128 \(\pm\) 15 | 4.8 \(\pm\) 0.3 | 3.1 \(\pm\) 0.5 |

#### TABLE 3

Emission Intensities and Derived Hydrogen Gas Mass within Radius \(\lesssim 5''\) Region

| Line    | Total Flux (Jy) | \(\int T_{\text{mb}}\, dv\) (K km s\(^{-1}\)) | Column Density \((10^{22}\, \text{cm}^{-2})\) | Hydrogen Gas Mass \((10^7\, M_\odot)\) |
|---------|----------------|---------------------------------|---------------------------------|-------------------------------|
| 12CO    | 251 \(\pm\) 5 | 2478 \(\pm\) 49 | 2.07 \(\pm\) 0.04 | 3.22 \(\pm\) 0.06 |
| 13CO    | 29 \(\pm\) 1 | 323 \(\pm\) 15 | 1.94 \(\pm\) 0.09 | 3.0 \(\pm\) 0.1 |
| C\(^{18}\)O | 11 \(\pm\) 1 | 128 \(\pm\) 15 | 4.8 \(\pm\) 0.3 | 3.1 \(\pm\) 0.5 |
of the central molecular gas and dust disk. Thus, if the dust emitting at 1.3 mm can be used as a proxy for that emitting at far-IR wavelengths, the bulk of this dust is likely heated by the circumnuclear starburst. Observations at higher angular resolutions are required to search for any dust heated by the central AGN and to study the very inner structure.

4.2. Central Molecular Concentration

4.2.1. The Central Disk

Our observation spatially resolves the central molecular gas concentration as traced in CO into an inclined rotating disk. The radius of this disk, measured over the region where it exhibits rigid-body rotation, is \( \sim 5'' \) (\( \sim 95 \) pc), although the central CO-emitting region extends beyond this radius. The overall radial size of the emitting region in \( ^{12}\text{CO}(2-1) \) is 8.2'' (156 pc), which is similar to that inferred from spatially unresolved single-dish observations by Dahlem et al. (1993). Their PV-diagram along the major axis of NGC 4945 (their Fig. 3) shows two local intensity peaks at velocities of \( \sim 430 \) and \( \sim 710 \) km s\(^{-1} \) separated by 16'' \(+6''\), interpreted as the two cross sections of a highly inclined ring. Our PV-diagram (Fig. 5) also shows two local intensity peaks near these velocities, specifically at 470 and 730 km s\(^{-1} \), separated (as measured from their centroids) by \( \sim 13'' \). These local intensity peaks in the PV-diagram correspond to the location where the rotation curve changes from rigid body to nearly flat, rather than tracing local spatial peaks corresponding to the two cross sections of an inclined ring. Our spatially resolved observations show no evidence for a central hole (or depression) in \( ^{12}\text{CO}(2-1) \), nor in \( ^{12}\text{CO}(2-1) \) or \( ^{13}\text{CO}(2-1) \), thus placing an upper limit of 2.2'' (42 pc) on the radius of any such hole.

The central molecular concentration is therefore a disk or torus (if it has a spatially unresolved central hole) rather than a ring. If it has a thickness much smaller than its observed dimensions, then the disk must have an inclination of \( 62'' \pm 2'' \) to the plane of the sky as measured in \( ^{12}\text{CO}(2-1) \), where the disk is least contaminated by surrounding features exhibiting noncircular rotation (see \S 4.2.2 and below). This is significantly different from the inclination of the large-scale galactic disk of \( \sim 78' \). Observations in H\(^i\) gas also indicate a small change in the inclination of the galactic disk with radius (Ott et al. 2001).

As mentioned in \S 1, Cunningham & Whiteoak (2005) measured a size for the central molecular concentration in HCN(1–0) of \( 8.5'' \times 4.2'' (\pm 0.5'') \) and a major axis at PA = 64'. This is only about one-half of the size that we measured in \( ^{12}\text{CO}(2-1) \) of \( 16.4'' \times 10.8'' (\pm 0.1'') \). As in previous observations, Cunningham & Whiteoak (2005) attribute the observed HNC(1–0) emission to the two cross sections of an edge-on ring or edge-thickened disk. Instead, our results suggest that the HNC(1–0) emission originates from the inner region of the disk that we observe here in CO. The critical density of molecular hydrogen gas for collisional excitation of HNC(1–0) is \( \sim 10^4 \) \( \text{cm}^{-3} \), which is about an order of magnitude higher than that for \( ^{12}\text{CO}(2-1) \) of \( \sim 10^3 \) \( \text{cm}^{-3} \). The excitation temperatures of these two species, however, are comparable. The smaller size of the disk in HNC(1–0) compared with that in \( ^{12}\text{CO}(2-1) \) therefore suggests a radial
decrease in (average) density with radius. Mauersberger et al. (1996) reached the same conclusions from a comparison of the line intensities and sizes for the central source in \( ^{12}\text{CO}(1-0) \), \( ^{12}\text{CO}(2-1) \), and \( ^{12}\text{CO}(3-2) \). In addition, the average gas density on the northeastern side of the disk is a factor of a few higher than that on the southwestern side (§ 3.2.4).

The peaks in HNC(1−0) emission (Fig. 11 of Cunningham & Whiteoak 2005) span approximately the same range of radii as the Pa\( \alpha \) starburst ring. We therefore associate this dense molecular gas with fueling the circumstellar starburst. The disk that we observe in CO extends beyond the starburst ring and therefore traces more diffuse gas in the disk at densities \( \sim 10^3 \text{ cm}^{-3} \) (§ 3.2.4). With an estimated star formation rate of \( \sim 0.4 \, M_\odot \text{ yr}^{-1} \) (Moorwood & Oliva 1994), compared with a mass in molecular gas for the disk of \( \sim (1-2) \times 10^8 \, M_\odot \), the circumstellar starburst must therefore be a transient phenomenon (lasting no longer than \( \sim 10^8-10^9 \) yr) if the disk is not replenished from its surroundings.

The dynamical mass of the disk within a radius of \( 5\arcsec \) (95 pc), where the disk exhibits circular rotation, is \( \sim 4 \times 10^8 \, M_\odot \). Using the method described in § 3.2.3, we infer a molecular gas mass within this region of \( \sim 3.1 \times 10^7 \, M_\odot \) (from C\( ^{18}\text{O} \)), which is about 13 times lower. The dynamical mass within a radius of \( 0.3\arcsec \) (5.7 pc) of the central supermassive black hole as inferred from H\( ^2\text{O} \) masers is \( 1.0 \times 10^6 \, M_\odot \) (Greenhill et al. 1997). The central region of the disk within a radius of \( 5\arcsec \) (95 pc) must therefore be dominated in mass by stars or, less likely, by gas not in molecular form.

4.2.2. A Surrounding Bar

The S-shaped asymmetry in the isovelocity contours of the intensity-weighted \( ^{12}\text{CO}(2-1) \) mean-velocity map (Fig. 4) resembles that seen extending to much larger scales in both molecular and atomic hydrogen gas. Ott et al. (2001) have imaged the entire disk of NGC 4945 in both \( ^{12}\text{CO}(2-1) \) and H\( \text{I} \) at comparable angular resolutions of \( \sim 24\arcsec \) with the SEST and Australia Telescope Compact Array (ATCA), respectively. They reported a similar antisymmetric distortion in the isovelocity contours around the central concentration, extending outward to \( 100\arcsec-200\arcsec \) in H\( \text{I} \). Ott et al. (2001) attribute these distortions to a (nearly edge-on) bar. If correct, then this bar must extend inward (almost) to the central disk and may be responsible for channeling gas inward to form this disk.

4.2.3. The Inner Kinematically Decoupled Component

The spatially unresolved but kinematically decoupled inner component described in § 3.2.1 spans approximately the same range of velocities as the surrounding disk. We have conducted the following check to make sure that this feature is not an artifact of the finite angular resolution of our observation. If within a radius of \( 5\arcsec \) the central concentration can be described by just a disk in rigid-body rotation, then the PV-diagram along its minor axis should show only emission at those velocities within the synthesized beam. For a radial velocity gradient as measured from the PV-diagrams along the major axis in \( ^{12}\text{CO}(2-1) \) and C\( ^{18}\text{O}(2-1) \) of \( \sim 27 \text{ km s}^{-1} \) arcsec\(^{-1} \) and with a width for the synthesized beam along the major axis of \( 4.4\arcsec \), the PV-diagram along the minor axis should therefore show velocities of only 520–640 km s\(^{-1} \). Instead, irrespective of the PA of the cut through the center of the disk, the inner feature spans velocities of 420–760 km s\(^{-1} \).

The gas density of the inner component as inferred in § 3.2.4 is sufficiently high to excite emission in the \( J = 1 \rightarrow 0 \) transitions of HCN, HCO\(^+ \), and HNC as observed by Cunningham.
& Whiteoak (2005). Indeed, their channel map in HNC (which suffers least from line absorption against the central continuum source) shows emission at or near the centroid of the disk even at the largest blueshifted and redshifted velocities of 370 and 750 km s\(^{-1}\). Similarly, their PV-diagram in HNC along the major axis of the disk shows that, even at disk center, the emission spans a broad range of velocities comparable with the range observed for the inner kinematically decoupled component. Because Cunningham & Whiteoak (2005) do not show a PV-diagram along the minor axis of the disk, however, we cannot be entirely sure that the inner component that we detected in CO was also detected in HNC.

What is the nature of this inner kinematically decoupled component? The near-IR vibrational line of molecular hydrogen traces the walls of a conically shaped cavity with roughly the same lateral size as the P\(\alpha\) starburst ring, attributed to a super-bubble blown by supernova-driven winds (Marconi et al. 2000). The inner kinematically decoupled feature may therefore correspond to the cooler component of the molecular outflow. If extending to the same height as the outflow seen in the near-IR vibrational line of molecular hydrogen (\(~3.6'\)), such an outflow would have been barely resolved in our observation (with an angular resolution of 3.3'' perpendicular to the major axis of the disk). As mentioned in \(?\ 3.2.4\), we infer a density for this inner kinematically decoupled component that is \(1-2\) orders of magnitude higher than that of the surrounding disk. This is contrary to expectations if the inner component corresponds to molecular gas entrained from the disk or surrounding gas.

A more attractive explanation is that this inner kinematically decoupled component comprises a separate rotating disk. This may naturally explain the relatively high density of \(\sim 10^{5}\) cm\(^{-3}\) (\(?\ 3.2.4\) inferred for the inner component. The range in velocities exhibited by the inner component is similar to that exhibited by the water masers around the AGN spanning 440–800 km s\(^{-1}\) (Greenhill et al. 1997), suggesting a connection between the two. If it has a radius of 1.4'' (\(?\ 3.2.1\)), the dynamical mass of such an inner disk would be \(~2 \times 10^6\ \text{M}_\odot\); if the actual radius is smaller, the corresponding dynamical mass would also be smaller. By comparison, the dynamical mass inferred from the H\(_2\)O megamasers is \(1.0 \times 10^6\ \text{M}_\odot\), which is about \(2\) orders of magnitude smaller still.

The column density of intervening neutral gas derived from X-ray absorption toward the AGN is \(\sim 10^{24.7}\) cm\(^{-2}\) (Iwasawa et al. 1993). This is about \(2\) orders of magnitude higher than the column density of molecular hydrogen gas inferred for the central disk of \(\sim 10^{22.8}\) cm\(^{-2}\) (\(?\ 3.2.3\)). If the bulk of the absorption originates from the large-scale galactic disk which in H\(\alpha\) has a radius of \(~11.4\) kpc (Ott et al. 2001), then the average density in this disk is required to be \(~140\ \text{cm}^{-3}\). This is about \(2\) orders of magnitude higher than the typical density in the interstellar medium of \(~1\ \text{cm}^{-3}\), and so the bulk of the X-ray absorption is unlikely to originate from the galactic disk. Instead, this X-ray absorption may originate from the inner kinematically decoupled component. As mentioned in \(?\ 3.2.4\), the denser part of inner component has densities of at least \(\sim 5 \times 10^{-1}-1 \times 10^5\) cm\(^{-3}\). To produce the required column density in X-ray absorption, this part of the inner component would then need to span a radius of roughly \(~20\) pc and, hence, have a mass of \(~10^7\ \text{M}_\odot\). If at this radius the inner component has a rotational velocity of \(85\) km s\(^{-1}\), corresponding to half the full range of velocities measured for this component, the enclosed dynamical mass within this radius would then be \(~10^7\ \text{M}_\odot\), comparable to its estimated mass in molecular gas.

The required properties of the denser part of the inner component necessary to produce the observed X-ray absorption are comparable with the size and rotational velocity (and hence also enclosed dynamical mass) of a highly inclined rotating disk in radio recombination lines imaged by Roy et al. (2005). This disk has its major axis aligned with the large-scale galactic disk, and an ionized gas mass of \(10^7-10^8\ \text{M}_\odot\). If the denser part of the inner component corresponds to the same disk imaged in radio recombination lines, then this disk must be composed primarily of molecular gas. This dense inner component may therefore be the hypothesized circumnuclear molecular torus invoked by AGN unification models. In the case of NGC 4945, which harbors a Seyfert 2 nucleus, the circumnuclear molecular torus is required by AGN unification models to be viewed at a large inclination to its rotation axis, as appears to be the case for the disk imaged in radio recombination lines.

5. SUMMARY AND CONCLUSIONS

Previous single-dish maps in the \(J = 1 \rightarrow 0, 2 \rightarrow 1,\) and \(3 \rightarrow 2\) transitions of \(^{12}\text{CO}\) infer the presence of a spatially unresolved molecular ring at the center of NGC 4945. The inferred radius of this ring ranges from \(~5''\) at the highest transition to \(~15''\) at the lowest transition. We have made an interferometric map that properly resolves for the first time the molecular gas as traced in CO at the center of NGC 4945. Our images in the \(J = 2-1\) transition of \(^{12}\text{CO},\ ^{13}\text{CO},\) and \(^{18}\text{O}\) and continuum at 1.3 mm show:

1. A disk in all three lines that exhibits rigid-body rotation within a radius of \(~5''\) (\(~100\) pc). Beyond this radius the rotation curve flattens and the isovelocity contours exhibit an S-shaped distortion that can be traced in \(^{12}\text{CO}(2-1)\) to a radius of \(~170\) pc. There is no central hole in the disk with a radius larger than \(~2.2''\) (42 pc).

2. The entire disk has a mass in molecular gas of \(~1-2\) \times \(10^8\ \text{M}_\odot\). The dynamical mass of the disk within a radius of \(~5''\) \((\sim 100\) pc\)) where it exhibits circular rotation, is \(~4 \times 10^8\ \text{M}_\odot\). The mass of molecular gas within this radius is \(~3 \times 10^7\ \text{M}_\odot\) and the mass of the central supermassive black hole may not be larger than \(~1 \times 10^6\ \text{M}_\odot\) (Greenhill et al. 1997).

3. Based on the measured line ratios, the bulk of this disk likely has densities \(~10^3\) cm\(^{-3}\) and temperatures \(<100\ \text{K}\), in agreement with values inferred from single-dish observations in multiple molecular species.

4. The disk extends beyond the circumnuclear starburst ring seen in P\(\alpha\). The major axis of the disk is aligned with that of the starburst ring and the large-scale galactic disk, all of which have PA \(~45^\circ\). The disk is inclined by \(~62^\circ \pm 2^\circ\) from the plane of the sky, significantly smaller than the inclination of the larger-scale galactic disk of \(~78^\circ\).

5. A spatially unresolved and kinematically decoupled component at the center of the disk has been discovered in all three lines. This component spans velocities of \(420-760\) km s\(^{-1}\), which is approximately the same as the range of rotational velocities exhibited by the surrounding disk, a smaller disk imaged in radio recombination lines, and an even smaller disk in water megamasers. With an upper limit in projected radius as small as \(1.4''\) (27 pc), this component would not have been recognized in previous single-dish maps.

6. The bulk of the molecular gas in the inner kinematically decoupled component resides in two very different densities. The denser portion has a density that is \(~1-2\) orders of magnitude higher than that in the bulk of the surrounding disk.
The more diffuse portion has a density that is comparable to that in the bulk of the surrounding disk.

7. A nuclear continuum source dominated by dust with a radius of 4.9′ (93 pc), about one-half of that measured in $^{12}$CO(2–1). This source extends beyond the bright inner rim of the circumnuclear starburst ring to, and along some directions beyond, its detectable outer radius.

By comparison, an interferometric map in HNC(1–0), tracing molecular gas at a density of approximately an order of magnitude higher than the above-mentioned CO(2–1) lines, reveals an inclined rotating-disklike feature with a radius of 4″ (76 pc), interpreted as a ring with an inner radius of 3″ (57 pc; Cunningham & Whiteoak 2005).

We interpret our results in the following manner:

1. The primary heating agent of the dust is star formation rather than AGN activity. Marconi et al. (2000) infer that UV and soft-X-ray photons cannot penetrate beyond a radius of ~1.5″ (~30 pc) from the AGN, whereas the continuum source has a radius about 4 times larger that is comparable with the outermost extension of the starburst ring.

2. The S-shaped distortion in the isovelcity contours is likely caused by a bar seen nearly edge-on. A similar distortion but on larger spatial scales has been seen also in single-dish $^{12}$CO(2–1) maps and interferometric H i maps of the entire galaxy (Ott et al. 2001). In H i this distortion can be traced out to a radius of ~200″ (380 pc) and is attributed to a nearly edge-on bar. The S-shaped distortion seen in our CO(2–1) map suggests that this bar extends inward to within ~5″ of the center of the galaxy and may have been responsible for channeling gas inward to create or replenish the central molecular disk.

3. The molecular gas mapped in HNC(1–0) traces the inner denser region of the same disk that we map in CO. The radial extent of the HNC(1–0) gas is approximately the same as that of the circumnuclear starburst ring, and so this relatively dense gas is likely responsible for fueling the circumnuclear starburst. In the absence of any replenishment, at the present star formation rate all the available molecular gas in the disk would be consumed in $10^5$–$10^6$ yr.

4. The denser part of the inner kinematically decoupled component is a promising candidate for the circumnuclear molecular torus invoked by AGN unification models. If it is responsible for producing the bulk of the X-ray absorption seen toward the AGN, then this component would have a size comparable with a highly inclined disk imaged in radio recombination lines that has a radius of ~20 pc.

Given the measurements now at hand, it would be instructive to construct a dynamical model of NGC 4945 to determine whether the inferred large-scale bar is responsible for channeling gas inward to replenish the central molecular disk. As for the inner kinematically decoupled component, we have conducted follow-up observations at higher angular-resolutions to clarify the nature of this component and will report the results in a future paper.

We wish to thank all the SMA personnel in Hawaii, Cambridge, and Taipei for their enthusiastic help during the observations. We also thank A. Marconi for providing near-infrared images of NGC 4945, and M. Wang for the VERITAS single-dish spectrum. J. Lim and S. Matsushita acknowledge support from the National Science Council of Taiwan for conducting this work. The Submillimeter Array is a joint project between the Smithsonian Astrophysical Observatory and the Academia Sinica Institute of Astronomy and Astrophysics and is funded by the Smithsonian Institution and the Academia Sinica.

Facilities: SMA

REFERENCES

Aalto, S., Booth, R. S., Black, J. H., & Johansson, L. E. B. 1995, A&A, 300, 369
Amari, S., Zinner, E., & Lewis, R. S. 1995, ApJ, 447, L147
Antonucci, R. 1993, ARA&A, 31, 473
Bergman, P., Aalto, S., Black, J. H., & Rydbeck, G. 1992, A&A, 265, 403
Bratza, J. A., Wilson, A. S., & Henkel, C. 1997, ApJS, 110, 321
Brock, D., Joy, M., Lister, D. F., Harvey, P. M., & Ellis, H. B., Jr. 1988, ApJ, 329, 208
Cunningham, M. R., & Whiteoak, J. B. 2005, MNRAS, 364, 37
Curran, S. J., Johansson, L. E. B., Bergman, P., Heikkila, A., & Aalto, S. 2001, A&A, 367, 457
Dahlem, M., Golla, G., Whiteoak, J. B., Wielebinski, R., Huettner, S., & Henkel, C. 1993, A&A, 270, 29
Done, C., Madejski, G. M., & Smith, D. A. 1996, ApJ, 463, L63
Downes, D., Radford, S. J. E., Guilloteau, S., Guelin, M., Greve, A., & Morris, D. 1992, A&A, 262, 424
Elmouttie, M., Haynes, R. F., Jones, K. L., Ehle, M., Beck, R., Harnett, J. I., & Wielebinski, R. 1997, MNRAS, 284, 830
Flowar, D. R., & Launay, M. J. 1985, MNRAS, 214, 271
Goldreich, P., & Kwan, J. 1974, ApJ, 189, 441
Greenhill, L. J., Moran, J. M., & Herrnstein, J. R. 1997, ApJ, 481, L23
Henkel, C., & Mauersberger, R. 1993, A&A, 274, 730
Henkel, C., Whiteoak, J. B., & Mauersberger, R. 1994, A&A, 284, 17
Hildebrand, R. H. 1983, QJRAS, 24, 267
Ho, P. T. P., Moran, J. M., & Lo, F. 2004, ApJ, 616, L1
Iwasawa, K., Koyama, K., Awaki, H., Kumieda, H., Makishima, K., Tsuru, T., Ohashi, T., & Nakai, N. 1993, ApJ, 409, 151
Karachentsev, I. D., et al. 2007, AJ, 133, 504
Lo, K. Y. 2005, ARA&A, 43, 625
Madejski, G., Zykri, R., Done, C., Valinia, A., Blanco, P., Rothschild, R., & Turek, B. 2000, ApJ, 535, L87
Marconi, A., Oliva, E., van der Werf, P. F., Maiolino, R., Schreier, E. J., Macchetto, F., & Moorwood, A. F. M. 2000, A&A, 357, 24
Mauersberger, R., Henkel, C., Whiteoak, J. B., Chin, Y.-N., & Tieferkun, A. R. 1996, A&A, 309, 705
McKee, C. F., Storey, J. W. V., Watson, D. W., & Green, S. 1982, ApJ, 259, 647
Meier, D. S., & Turner, J. L. 2004, AJ, 127, 2069
Moorwood, A. F. M., & Oliva, E. 1994, ApJ, 429, 602
Ott, M., Whiteoak, J. B., Henkel, C., & Wielebinski, R. 2001, A&A, 372, 463
Paglione, T. A. D., et al. 2001, ApJS, 135, 183
Papadopoulos, P. P., & Seacquist, E. R. 1998, ApJ, 492, 521
Roy, A. L., Goss, W. M., Niruj, R. M., Oosterloo, T., & Anantharamaiah, K. R. 2005, in AIP Conf. Proc. 783, The Evolution of Starbursts, ed. S. Huettner et al. (Melville: AIP), 303
Sage, L. J., Mauersberger, R., & Henkel, C. 1991, A&A, 249, 31
Sakamoto, K., et al. 2006, ApJ, 636, 685
Scrich, N. J., Roberts, T. P., & Warwick, R. S. 2002, MNRAS, 335, 241
Solomon, P. M., Scoville, N. Z., & Sanders, D. B. 1979, ApJ, 232, L89
Wall, W. F., Jaffe, D. T., Basu, F. N., Israel, F. P., Maloney, P. R., & Baas, F. 1993, ApJ, 414, 98
Wang, M., Henkel, C., Chin, Y.-N., Whiteoak, J. B., Hunt Cunningham, M., Mauersberger, R., & Mauders, D. 2004, A&A, 422, 883
Webster, B. L., Goss, W. M., Hawarden, T. G., Longmore, A. J., & Mebold, U. 1979, MNRAS, 186, 31
Weiss, A., Neininger, N., Huettner, S., & Klein, U. 2001, A&A, 365, 571
Whiteoak, J. B., Dahlem, M., Wielebinski, R., & Henkel, J. I. 1990, A&A, 231, 25
Whiteoak, J. B., & Wilson, T. L. 1990, MNRAS, 245, 665