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CO 7 → 6 SUBMILLIMETER EMISSION FROM THE GALACTIC CENTER: WARM MOLECULAR GAS AND THE ROTATION CURVE IN THE CENTRAL 10 PARSECS

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ABSTRACT

We have mapped bright CO $J = 7 \rightarrow 6$ submillimeter line emission in the central 10 pc of the Galaxy. This is the first detection of the $7 \rightarrow 6$ line from the Galactic center, made with a newly constructed submillimeter heterodyne spectrometer. The 372 μm CO emission comes from a dense, clumpy disk ($n_H \approx 3 \times 10^4$ cm^{-3}, mass $\approx 10^4$ $M_\odot$) of temperature $\sim$ 300 K. The luminosity of all CO rotational lines emitted from this $\sim 4'$ diameter region is about 2×10^4 $L_\odot$. CO line emission is a major contribution to the cooling of the interstellar gas near Sgr A. Mass outflow from the center or cloud-cloud collisions may cause shocks which heat the warm molecular gas. The kinetic energy dissipation rate in shocks necessary is $\geq 2 \times 10^5$ $L_\odot$. This requires a very large mass-loss rate ($\gtrsim 0.5$ $M_\odot$ yr^{-1}) or efficient regeneration of cloud-cloud turbulence throughout the region on a very short time scale ($\leq 5 \times 10^3$ yr). Alternatively, UV radiation from the Galactic center could heat the molecular gas if CO self-shielding is effective. The CO abundance must then be $\sim 10^{-4}$ in the "photodissociation" region ($A_v \leq 5$), where most of the UV energy is absorbed.

The CO data show that the rotational velocities drop by a factor of 1.4 to 2 between 2 and 6 pc from the center. The rotation curve is consistent with a "Keplerian" fall off around a point mass and implies that most of the mass is in a more compact distribution than an isothermal stellar cluster. Broad line width emission toward the central 30″ of the Galaxy indicates that there is a significant amount of molecular material in the inner, mostly ionized, cavity.

Subject headings: galaxies: nuclei — infrared: sources — interstellar: matter — interstellar: molecules

I. INTRODUCTION AND OBSERVATIONS

Observations of far-infrared continuum and fine-structure line emission (Becklin, Gatley and Werner 1982; Genzel *et al.* 1984, 1985) have shown that a rotating disk or ring of warm atomic gas and dust surrounds the center of the Galaxy. The inner radius of the disk is $\sim$ 2 pc, the outer radius is $\geq$ 5 pc, and the total mass of gas within 5 pc from the center is $\sim 2 \times 10^4$ $M_\odot$. The detection of 2 μm emission from molecular hydrogen (Gatley *et al.* 1984*a*) and of far-IR emission from CO and OH (Genzel *et al.* 1985) indicate that this region also contains highly excited molecular material. The neutral disk surrounds an ionized cavity of low average density which is largely transparent to the ultraviolet (UV) radiation from the center (Becklin, Gatley, and Werner 1982). This UV radiation probably heats the atomic gas in the neutral disk (Genzel *et al.* 1985), and shocks may excite the molecular gas (Gatley *et al.* 1984*a*).

We obtained the CO $J = 7 \rightarrow 6$ spectra shown in Figure 1 in 1984 June with the recently constructed UC Berkeley Cassegrain Submillimeter Spectrometer, mounted on the 3.0 m NASA IRTF telescope at Mauna Kea, Hawaii. The spectrometer (Jaffe *et al.* 1985; Harris *et al.* 1985) is an open structure receiver with a room temperature Schottky diode mixer mounted in a corner cube structure, a cooled first IF, and molecular laser local oscillator. The backend is a standard filter spectrometer with 64×20 MHz channels, providing velocity resolution of 7.4 km s^{-1} per channel over $\sim$ 480 km s^{-1}. At the 806.6519 GHz (371.6504 μm) CO rest frequency, the system temperature on the telescope was about 13,000 K (SSB). The measured beam was approximately Gaussian with a FWHM of 32″. Aperture and main beam efficiencies were 40% and 45%, determined from observations of Mars, Jupiter, and the Moon. We determined the atmospheric transmission approximately hourly by measuring the sky temperature at different zenith angles and assuming that the physical temperature of the sky was 273 K. The zenith transmission on 1984 June 13 was $\sim$ 30% with a *relative* variation of ± 1%, resulting in a transmission along the line of sight toward Sgr A of $\sim$ 14%. The zenith atmospheric transmission on June 14 was $\sim$ 12.5%. With the exception of the topmost spectrum in Figure 1 (obtained on June 14), all data were obtained in $\sim$ 10 minutes per point integrations on June 13. The telescope's chopping secondary switched 190″ at 17 Hz along an east-west line, which is about 70° off the Galactic plane. The vertical scale in Figure 1 is Rayleigh-Jeans main beam brightness temperature, that is, hot-cold load calibrated antenna temperature corrected for atmospheric transmission and divided by the main beam efficiency. The absolute uncertainty of the brightness temperature scale, including transmission uncertainties, is ± 30%; relative intensities are uncertain to ± 15%.

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All positions given in Figures 1 and 2 are in galactic coordinates relative to the radio point source at R.A. = $17^h42^m29^s.3$, decl. = $-28°59'19''$(1950) (pointing accuracy $\pm 5''$). In the following analysis we take the distance to the galactic center as 10 kpc (20″ per pc).

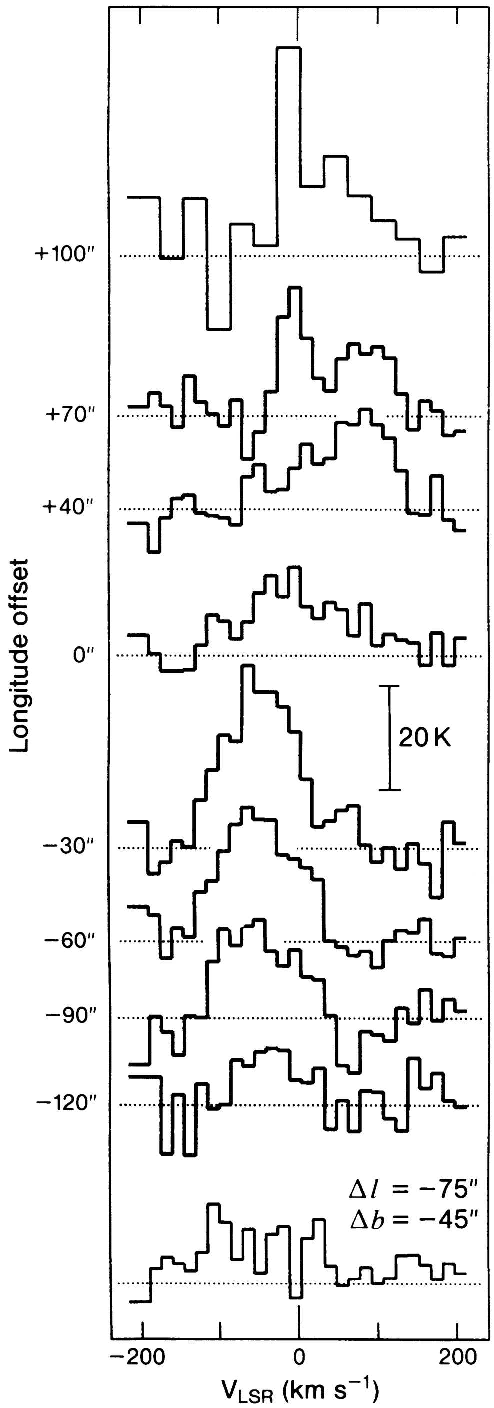

FIG. 1.—Spectra of the $J = 7 \rightarrow 6$ transition of CO at 806 GHz (beam size 32″) toward eight positions along the Galactic plane, and one position (*bottom*) near the blueshifted $1 \rightarrow 0$ emission peak reported by Liszt *et al.* (1983). The position offsets are relative to the radio point source. The intensities are in units of degrees Rayleigh-Jeans main beam brightness temperature. The spectra have a resolution of 14.8 km s^{-1}, with the exception of the topmost spectrum which has a resolution of 29.6 km s^{-1}.

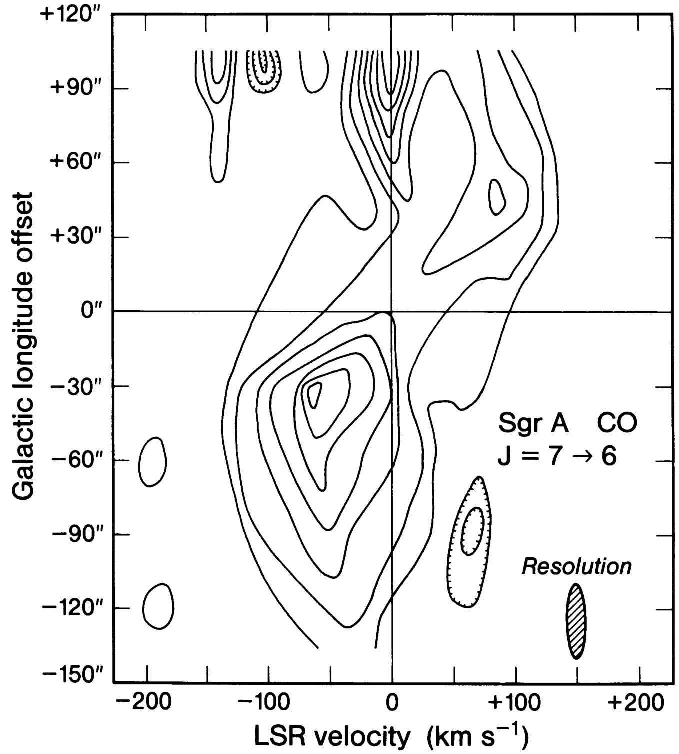

FIG. 2.—*l-v* diagram constructed from the eight top spectra (along the plane) of Fig. 1. The data were smoothed to an effective resolution of ~ 20 km s^{-1}. The negative contours at LSR ≈ 50 km s^{-1} and $\Delta l \approx -90''$ are probably due to emission in the reference beam.

II. RESULTS

Figure 1 shows the CO $7 \rightarrow 6$ spectra at several positions along the Galactic plane and one point slightly off the plane near the peak of $1 \rightarrow 0$ CO emission at $v_{LSR} \approx -50$ to -120 km s^{-1} (Liszt *et al.* 1983). Figure 2 shows the *l-v* diagram derived from the data. Figure 3 gives the integrated intensities of different rotational lines of CO toward the peak of the $7 \rightarrow 6$ CO emission ($\Delta l = -30''$).

a) *Spatial Distribution*

The line profiles, source size (~ 7 pc FWHM) and spatial distribution along the Galactic plane of the submillimeter CO emission are very similar to those of the far-IR [C II] and [O I] fine-structure lines (Lugten *et al.* 1985; Genzel *et al.* 1985). Clearly, the warm molecular and atomic gas are closely associated throughout the neutral disk.

b) *Physical Conditions of the Molecular Gas*

The submillimeter CO emission comes from warm and dense gas. The $J = 7 \rightarrow 6$ line has a peak Rayleigh-Jeans main beam brightness temperature of 35 K, which sets an absolute lower limit to the gas temperature of 52 K if the line is thermalized ($n_{H_2} > 10^4$ cm^{-3}) and optically thick. The relative ratios of the line intensities of the $1 \rightarrow 0$, $2 \rightarrow 1$, $7 \rightarrow 6$, $16 \rightarrow 15$, and $20 \rightarrow 19$ CO transitions (Fig. 3) constrain the physical parameters of the molecular gas at the $7 \rightarrow 6$ peak. We have computed the level populations of the lowest 30 rotational levels of CO as a function of density and temperature, assuming statistical equilibrium and using the cross sections given by McKee *et al.* (1982). The computations

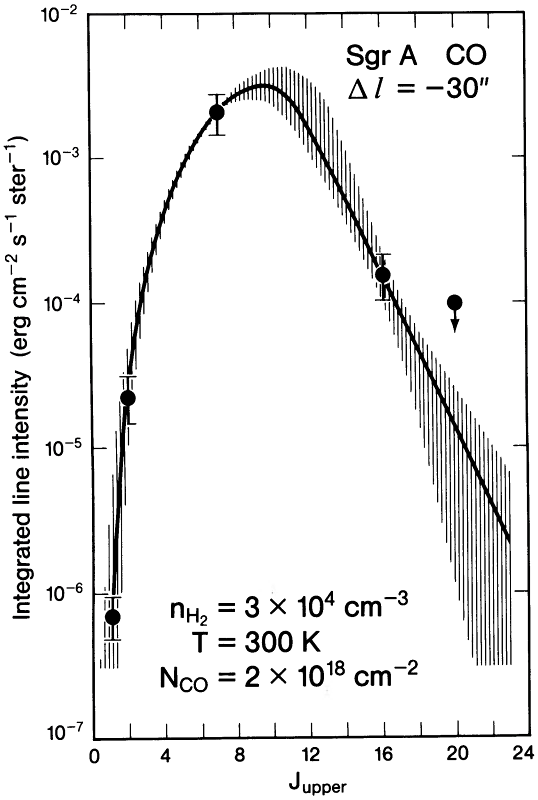

FIG. 3.—Integrated line intensities of CO rotational lines toward the 7 → 6 emission peak ($\Delta l = -30''$). The 7 → 6 data are from this paper, the 1 → 0 measurement is from Liszt *et al.* (1983), 2 → 1 from Lo (private communication), 16 → 15 from Genzel *et al.* (1985), and 20 → 19 from Genzel (unpublished). The heavy solid line is the best fitting model with $N_{CO} = 2 \times 10^{18}$ cm^{-2}, $n_{H_2} = 3 \times 10^4$ cm^{-3}, $T_{gas} = 300$ K, and beam area filling factor ≥ 0.2. The hatched region gives the range of equally acceptable models, from $n_{H_2} = 10^4$ cm^{-3}, $T = 450$ K to $n_{H_2} = 5 \times 10^5$, $T = 150$ K.

include a large velocity gradient escape probability formalism to account for radiative transport. The best fitting parameters for the CO emission in a single component model are (Fig. 3): $n_{H_2} = 3 \times 10^4$ cm^{-3}, $T_{gas} = 300$ K, and beam-averaged column density $N_{CO} = 2 \times 10^{18}$ cm^{-2}. The 7 → 6 line has an optical depth ~ 1, while the 1 → 0, 2 → 1, and 16 → 15 lines are optically thin. With a molecular hydrogen column density of 2×10^{22} cm^{-2} in the neutral disk (Genzel *et al.* 1985), the CO abundance is 10^{-4}. The relatively low column densities compared with the high volume densities derived above imply that the CO emission region is highly clumped with a volume filling factor of ~ 0.1 and a beam area filling factor of $\gtrsim 0.2$. Figure 3 shows that temperature-density combinations ranging from $n_{H_2} = 5 \times 10^5$ cm^{-3}, $T = 150$ K to $n_{H_2} = 10^4$ cm^{-3}, $T = 450$ K also give acceptable fits to the data. The density (10^5 cm^{-3}) and temperature (350 K) estimated for the warm atomic gas in the Galactic center (Genzel *et al.* 1985) fall within this range.

Multiple-component models of the CO emission with a range of temperature and density are also possible but do not change the major results above. For example, a combination of 2×10^{18} cm^{-2} of 150 to 200 K CO gas with a smaller column ($\sim 10^{17}$ cm^{-2}) of hotter gas ($T \leq 800$ K) could also account for the data. However, *most* of the $\sim 10^4$ $M_\odot$ of molecular gas in the neutral disk around Sgr A *must be warmer* than ~ 150 K to account for the 7 → 6 line intensity and the 7 → 6 to 2 → 1 and 1 → 0 ratios.

Spatial variations of the line ratios of the 7 → 6 to the 1 → 0 and 16 → 15 lines suggest that the physical parameters of the molecular gas vary along the Galactic plane. Compared to $\Delta l = -30''$, the molecular gas pressure (estimated from the 7 → 6 to 1 → 0 or 7 → 6 to 16 → 15 line ratios together with the collisional model referred to above) is larger by a factor of ~ 1.4 at the central position and by a factor of ~ 2 at $\Delta l = +40''$. On a larger scale, gas pressure appears to drop with increasing distance on either side of the center, corresponding to a falloff of $n_{H_2}T$ by 2–3 between $\Delta l = -30''$ and the CO 1 → 0 peak at $\Delta l = -75''$, $\Delta b = -45''$.

c) *Total* CO *Luminosity*

The high brightness of the CO line indicates that the CO rotational lines are important coolants of the interstellar gas near the center. The peak luminosity of the 7 → 6 line in a 30″ beam is 2×10^2 $L_\odot$, and the luminosity integrated over the source is $\sim 2 \times 10^3$ $L_\odot$. The total CO rotational line cooling is $L_{CO}^{tot} \approx 2 \times 10^4$ $L_\odot$ (from Fig. 3), about one order of magnitude greater than the cooling in the 7 → 6 line alone, and about 0.4% of the observed luminosity from Sgr A West.

d) *Kinematics*

The far-infrared measurements of the [O I] and [C II] fine-structure lines imply that the neutral gas disk rotates at ~ 100 km s^{-1} and has an inner radius ~ 2 pc. The disk's plane is inclined by 20° relative to the line of sight and by −20° relative to the galactic plane. Its rotation axis is close to that of the Galaxy at much larger scales. The CO data in Figures 1 and 2 are in excellent agreement with this model. The velocity gradient and terminal velocities of the CO emission between $\Delta l = -40''$ and $\Delta l = +40''$ indicate that molecular gas is abundant at the inner edge of the neutral disk. The longitude extent of the CO emission shows that the outer radius of the disk is ≥ 6 pc.

The CO data give an estimate of the rotation curve between 2 and 6 pc. On either side of the center, velocity centroids as well as terminal velocities drop by a factor of 1.4–2 over this range of radii. This decrease is consistent with a "Keplerian" ($R^{-1/2}$) fall-off of rotational velocity around a point mass. If an extended stellar cluster dominates, the stellar density must decrease at least as fast as $R^{-2.6}$, thus excluding an isothermal distribution (R^{-2}). Depending on the correction for broadening of the line profiles by noncircular gas motion (see below) and the orientation of the rotation axis of the disk in the plane of the sky, a mass between 3 and 9×10^6 $M_\odot$ lies within a radius of 2 pc from the center. Our best estimate is 5×10^6 $M_\odot$.

There are clear deviations from the simple picture of a rotating disk. Different projected velocities along the line of sight through the disk can only partly explain the broad line widths at most positions (FWHM ≈ 100 km s^{-1}). The slow drop-off of the line profiles from the peaks to the terminal velocities and the presence of redshifted emission at all positions with negative longitude suggest that there are substantial non-circular motions. For example, the small clumps may move randomly with respect to each other and there may be larger scale radial motions. Judging from the line profiles in Figure 1, the line broadening due to these noncircular motions is probably between 30 and 50 km s^{-1} (FWHM). CO submillimeter emission is also present from features probably not associated with the neutral disk. The strong narrow peak at LSR ≈ 0 km s^{-1} north of the center and the emission and absorption in the reference beam at +20–50 km s^{-1} LSR at negative longitudes may come from molecular clouds along the line of sight to the center.

Broad line width emission (> 200 km s^{-1}) toward the central position suggests that there is also molecular gas *within* the central ionized cavity. This emission is probably not part of the rotating neutral disk and may come from the neutral cores of small clumps at $R \lesssim 1.7$ pc which are ionized on their surfaces. We estimate a beam-averaged CO column density of 2–8 × 10^{17} cm^{-2} and a total molecular mass of 0.5–2 × 10^2 $M_\odot$ ($[CO]/[H_2] = 10^{-4}$) within $R = 1.5$ pc. Hence, a significant fraction of the interstellar gas in the central cavity may be in molecular form.

III. DISCUSSION

We discuss the two main results of our submillimeter observations: (*a*) the existence of a large mass (~ 10^4 $M_\odot$) of dense, warm ($T \geq 150$ K) molecular gas, cooling at a rate of ≥ 2 × 10^4 $L_\odot$; and (*b*) evidence for a "Keplerian" fall-off of the rotational velocities of the neutral disk between 2 and 6 pc from the dynamical center.

a) Heating Mechanisms of the Molecular Gas

There are two likely heating mechanisms of the warm molecular gas: shocks and UV heating. Shock heating is a natural possibility, since 2 μm H_2 line emission has been detected toward the neutral gas disk in Sgr A (Gatley *et al.* 1984*a*). A 30–40 km s^{-1} C-type shock wave traveling into the molecular cloud can account for the 2 μm H_2 and far-infrared CO/OH emission in the Orion-KL region (Draine and Roberge 1982; Chernoff, Hollenbach, and McKee 1982). In the Galactic center, such shocks could result from mass outflow from the central 1 pc (Gatley *et al.* 1984*a*) or cloud-cloud collisions in the. disk (Genzel *et al.* 1985). There are two problems with shock heating: First, the total luminosity in all CO rotational lines is about a factor of 40 larger than the luminosity in all H_2 infrared lines inferred by Gatley *et al.* (1984*a*). In Orion-KL the CO cooling is about 0.1–0.5 times the H_2 cooling. The theoretical models by Draine, Roberge, and Dalgarno (1983) show that CO cooling is significantly less important than H_2 for most shock velocities and reaches about the same importance only for slow shocks ($v_s \leq 10$ km s^{-1}). Furthermore, the 2 μm H_2 $S(1)$ line emission in Sgr A comes from a thin ring of radius ≈ 2 pc (Gatley *et al.* 1984*b*), unlike the extended 7 → 6 CO emission. The second problem is the high luminosity of the total CO emission. The calculations of Draine, Roberge, and Dalgarno (1983) indicate that the CO cooling efficiency is significantly less than 10% for a CO abundance $\lesssim 10^{-4}$, implying that the shock dissipation rate in the Galactic center would have to be at least 2 × 10^5 $L_\odot$. If mass outflow from the center drives a 10 km s^{-1} shock into the neutral disk, the required mass-loss rate is ~ 0.5[(500 km s^{-1})/$v_{outflow}$] $M_\odot$ yr^{-1}. This mass loss rate is two orders of magnitude greater than can be accounted for by the high-velocity He I/H I gas near IRS 16 (Geballe *et al.* 1984). The high rate of energy consumption inferred from the CO data also is a problem if the shocks are produced in cloud-cloud collisions. If these shocks affect all of the ~ 10^4 $M_\odot$ of gas in the disk and turbulent energy is converted into CO radiation with an efficiency of 10%, the decay time of the turbulence in the disk—which is equal to the cloud-cloud collision time—is a few 10^3 yr, significantly smaller than the dynamical crossing time through the region (a few 10^4 yr). It is unlikely that any energetic mechanism (e.g., supernova explosions, mass infall, dynamical instabilities) can support the high energy dissipation rate in steady state.

Alternatively, UV heating could account for the excitation of the warm gas. The CO emission would come from gas in the "photodissociation" region of each small cloud in the disk, where the intense UV radiation from the center (~ 10^7 $L_\odot$) is converted into heat and far-infrared continuum and line radiation. The close coincidence in physical parameters and spatial distribution of the warm molecular gas and the atomic gas strongly suggests this possibility. Further support for a high abundance of CO in the UV-heated region may also come from the fact that CO may be present in the central 1.5 pc and from the relatively low C^+ abundance in the photodissociation region inferred by Genzel *et al.* (1985). To account for the observations, a CO abundance of ~ 10^{-4} within $A_v \lesssim 5$ of the cloud edge is required. Bally and Langer (1982) and Glassgold, Huggins, and Langer (1985) have shown that with effective shielding (as suggested by recent laboratory evidence), such a high CO abundance in the UV-heated "photodissociation" region ($1 \leq A_v \leq 5$) may be possible. Cooling by the CO rotational lines from this warm (100–300 K) gas may be enhanced by up to a factor of 10 compared to models without shielding (Tielens and Hollenbach 1985).

Other possible heating mechanisms are less likely. Heating by gas-grain collisions cannot account for the > 150 K gas temperatures in the disk since $T_{dust} \approx 50$ K (Becklin, Gatley, and Werner 1982). Cosmic-ray heating is also an unlikely mechanism since the heating rate required ($\xi \approx 10^{-12}$ s^{-1}) is far higher than reasonably possible in this region. The soft X-ray luminosity ($L < 10^{36}$ ergs s^{-1}; Watson *et al.* 1981) or hard X-ray luminosity ($L \ll 3 \times 10^{38}$ ergs s^{-1}; Matteson 1982) are not large enough to produce the observed CO luminosity.

b) Mass Distribution in the Central 10 Parsecs

Our results are in agreement with the observations and conclusions of Serabyn and Lacy (1985) and Genzel *et al.* (1985) who find that the mass enclosed within 1.7 pc is 4.7 ± 1 × 10^6 $M_\odot$. Serabyn and Lacy's observations of the ionized gas imply that the mass distribution between 0.5 and 1.7 pc is consistent with a point mass and requires a mass density distribution at least as concentrated as $R^{-2.7}$. The "Keplerian" fall-off of the rotational velocities at $R \geq 2$ pc reported here is confirmed by new observations of the 158 μm [C II] line (Lugten *et al.* 1985). Taken together, the infrared and submillimeter observations make a convincing case that most of the mass in the central 2 pc is in a massive black hole of ~ 4 × 10^6 $M_\odot$ surrounded by a stellar cluster containing 1–2 × 10^6 $M_\odot$ within 2 pc and $\lesssim$ 10 × 10^6 $M_\odot$ within 10 pc. This will be discussed in a separate report (Crawford *et al.* 1985).

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