THE ASTROPHYSICAL JOURNAL, 276:551–559, 1984 January 15


# FAR-INFRARED SPECTROSCOPY OF THE GALACTIC CENTER: NEUTRAL AND IONIZED GAS IN THE CENTRAL 10 PARSECS OF THE GALAXY

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*Received 1983 February 24; accepted 1983 June 17*

## ABSTRACT

We have mapped the $^3P_1$–$^3P_2$ fine structure line emission from neutral atomic oxygen at 63 $\mu$m in the vicinity of the galactic center. The emission is extended over more than 4′ (12 pc) along the galactic plane, centered on the position of Sgr A West. The line center velocities show that the O I gas is rotating around the galactic center with an axis close to that of the general galactic rotation, but there appear also to be noncircular motions. The rotational velocity at $R \sim 1$ pc corresponds to a mass within the central parsec of about $3 \times 10^6$ $M_\odot$. Between 1 and 6 pc from the center the mass is approximately proportional to radius.

The [O I] line probably arises in a predominantly neutral, atomic region immediately outside of the ionized central parsec of our Galaxy. Hydrogen densities in the [O I] emitting region are $10^3$ to $10^6$ cm$^{-3}$ and gas temperatures are $\geq 100$ K. The total integrated luminosity radiated in the line is about $10^5$ $L_\odot$, and is a substantial contribution to the cooling of the gas. Photoelectric heating or heating by ultraviolet excitation of $H_2$ at high densities ($\sim 10^5$ cm$^{-3}$) are promising mechanisms for heating of the gas, but heating due to dissipation of noncircular motions of the gas may be an alternative possibility.

We have also detected the $^3P_1$–$^3P_0$ fine structure line of [O III] at 88 $\mu$m toward Sgr A West. The [O III] emission comes from high-density ionized gas ($n > 10^4$ cm$^{-3}$), and there is no evidence for a medium-density region ($n < 10^3$ cm$^{-3}$), such as the ionized "halo" in Sgr A West deduced from radio observations. This radio halo may be nonthermal, or may consist of many compact, dense clumps or filaments on the inner edges of neutral condensations at $R \geq 2$ pc.

*Subject headings:* infrared: sources — interstellar: matter — galaxies: Milky Way — galaxies: nuclei

## I. INTRODUCTION

Emission in the 63 $\mu$m $^3P_1$–$^3P_2$ [O I] fine structure line from Sgr A West was detected by Lester *et al.* (1981). These earlier observations indicated that the [O I] line emission is associated with the galactic center, and has large line widths ($\Delta v \geq 200$ km s$^{-1}$). Lester *et al.* (1981) suggested that the emission arises either in partially ionized gas associated with the ionized central 3 pc of the Galaxy or, more likely, that the [O I] line comes from warm, neutral gas just outside the H II region Sgr A West. The [O I] emission is the first unambiguous indication of neutral gas within a few parsecs of the galactic center. In this paper we report more extensive observations, with better sensitivity and higher spectral resolution, to establish the angular distribution, kinematics, and excitation of the O I gas. In addition, we report the detection of the 88 $\mu$m $^3P_1$–$^3P_0$ line of doubly ionized oxygen toward Sgr A West and discuss its implication for the density distribution of ionized gas around the galactic center.

## II. OBSERVATIONS

The data were taken with the 91.4 cm telescope on board the NASA Kuiper Airborne Observatory between 1981 June 11 and 14. The spectrometer was a liquid helium cooled, tandem Fabry-Perot spectrometer described by Storey, Watson, and Townes (1980), with a photoconductive detector. The system noise equivalent power (NEP), including all atmospheric and instrumental losses, was $\sim 10^{-13}$ W Hz$^{-1/2}$. The angular resolution was 44″ FWHM (60″ equivalent disk), and the chopper throw was 5′.7 in azimuth of the airplane (50°–80° relative to the galactic plane 20°–50° W of N), with a chopping frequency of 29 Hz. The instrumental characteristics were as follows:

i) [O I]: The spectrometer's resolving power was set to $\lambda/\Delta\lambda = 2000$, resulting in a Lorentzian instrumental profile of FWHM 150 km s$^{-1}$. Relative wavelength and velocity calibration across the spectral scan was established by measuring interference fringes of a He-Ne laser at $\lambda = 0.632$ $\mu$m in reflection off the scanning Fabry-Perot metal mesh mirrors. Absolute wavelength calibration was provided by a strong $H_2O$ line at 63.3236 $\mu$m (McClatchey *et al.* 1973), and the rest wavelength of the [O I] line was taken to be 63.18372 ($\pm 3 \times 10^{-5}$) $\mu$m.[1] The precision of the [O I] line center velocities is about $\pm 15$ km s$^{-1}$, and that of the line widths

[1] The measured fine structure wavelength reported by Saykally and Evenson (1979, $\lambda$[O I] = 63.1700 $\mu$m) was based on an incorrect value of the 63.1 $\mu$m laser frequency. The correct laser frequency is 4751.3414 GHz, which shifts the [O I] wavelength from that reported by Saykally and Evenson by 65.0 km s$^{-1}$ to longer wavelength (Evenson, private communication).

$\pm 30$ km s$^{-1}$. At the observing altitude of 12.5 km, the boresight column density of precipitable water vapor varied between 15 and 25 $\mu$m. Since the [O I] line is separated from the telluric $H_2O$ line at 63.3236 $\mu$m by only 0.14 $\mu$m ($\sim$700 km s$^{-1}$), the effect of the water vapor was to substantially absorb any continuum and line emission more than 300 km s$^{-1}$ longward of the rest wavelength of [O I]. To check the influence of water vapor on the line shapes more quantitatively, we divided the Sgr A spectra by a spectrum of Sgr B2, which does not show [O I] emission. There was no significant change in center velocity or line width for the observed [O I] lines. Hence, with the possible exception of the most redshifted emission ($v_{LSR} > 200$ km s$^{-1}$) in the spectra north of the center, the [O I] profiles probably give a good representation of the kinematics of the [O I] gas. To determine the absolute line intensities, we used the observed line to continuum ratios and the continuum observations of Gatley *et al.* (1978) who report a 63 $\mu$m continuum flux of 9000 Jy in a 1′ beam at the peak of Sgr A. A comparison of the continuum intensity distribution derived from our data with the 100 $\mu$m continuum map of Gatley *et al.* indicates that our nominal (0, 0) position was at R.A. = $17^h29^m29^s$, decl. = $-28°59'$ (1950), about 15″–20″ north of Sgr A IRS 1. The relative positional accuracy of our various measurements is probably about $\pm 10''$.

ii) [O III]: The spectrometer's resolving power was set to $\lambda/\Delta\lambda = 1600$ at 88.356 $\mu$m, the rest wavelength of the [O III] $^3P_1$–$^3P_0$ line (Moorwood *et al.* 1980). The line intensity was determined by adopting an 88 $\mu$m continuum flux density of 8000 Jy in a 1′ beam at the peak of Sgr A (Gatley *et al.* 1978).

## III. RESULTS

### *a) Angular Distribution of the* [O I] *Emission*

The [O I] spectra taken at 12 positions spaced by about 40″ ($\sim$one beamwidth) along and across the plane are shown in Figure 1, as a function of offset from the nominal (0, 0) position. The integrated intensity of the line at the peak position is $1.7 \pm 0.5 \times 10^{-16}$ W cm$^{-2}$, in good agreement with the value reported by Lester *et al.* (1981). The corresponding [O I] luminosity at the peak position (for a distance of 10 kpc) is $5 \times 10^3$ $L_\odot$, and the integrated line intensity over the region mapped is around $\sim 10^5$ $L_\odot$. Cuts of line intensity, continuum intensity, and their ratios along and across the plane are shown in Figure 2. In this figure, we have also plotted the distribution of the dust emission at $\lambda \geq 50$ $\mu$m, when observed with

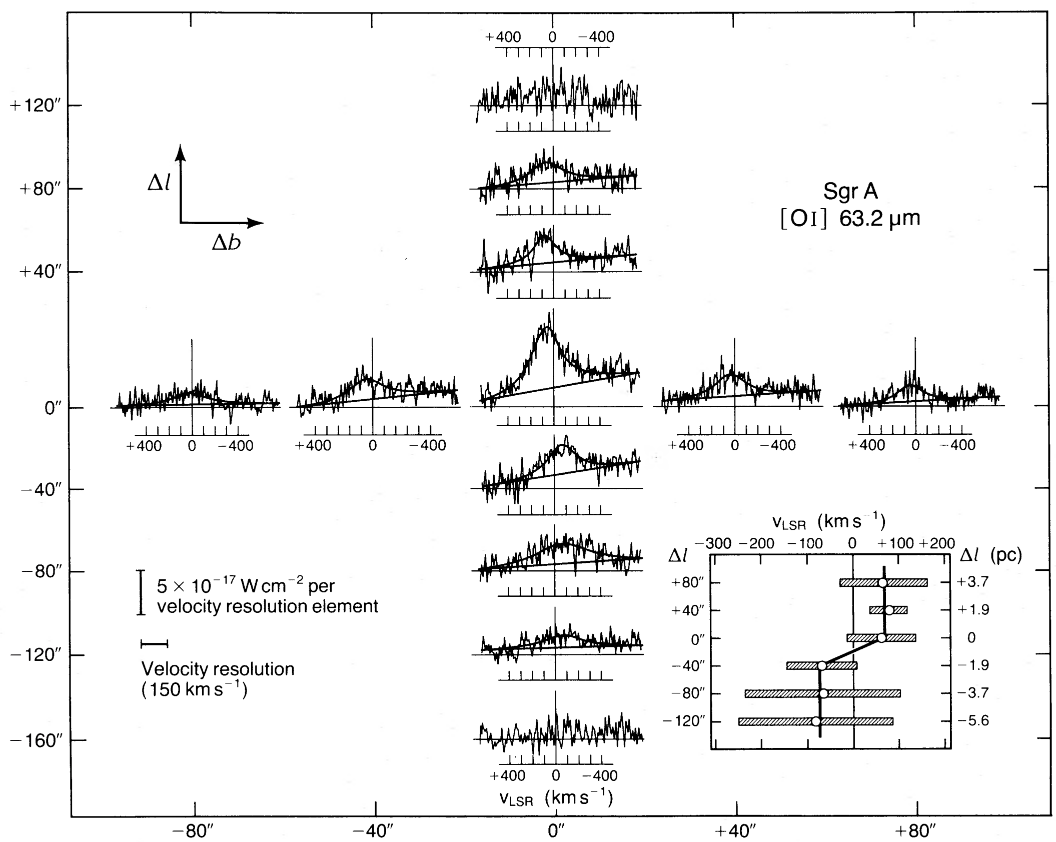


FIG. 1.—Observed spectra of the $^3P_1$–$^3P_2$ fine structure line of [O I] 63.184 $\mu$m toward Sgr A in a beam 44″ FWHM (60″ equivalent disk). Spectra are displayed as a function of offset from the zero position (in units of 40″) along the galactic plane (vertically) and perpendicular to the plane (horizontally). The (0, 0) position is: R.A. $17^h42^m29^s$, decl. = $-28°59'$ (1950), which is about 15″ to 20″ north of the galactic center. The instrumental profile is a Lorentzian with a velocity resolution (FWHM) of 150 km s$^{-1}$. Velocity resolution and intensity scale are indicated in the bottom left corner. The bottom right inset is a longitude-velocity (*l*-*v*) diagram of the line centroids (*shaped circles*) and the FWHM widths (*gray boxes*) of the [O I] lines, after deconvolution with the instrumental resolution of $\sim$150 km s$^{-1}$ (assuming Lorentzian line shapes). The diameters of the circles roughly indicate the uncertainties in line center velocities (typically $\pm 15$ km s$^{-1}$) and the relative pointing accuracy ($\pm 10''$). All velocities are relative to the local standard of rest (LSR).

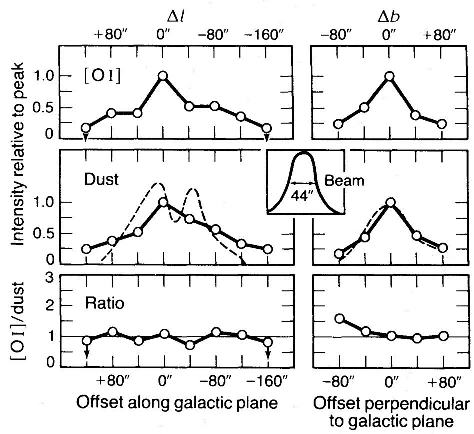


FIG. 2.—Cuts of observed [O I] line and continuum intensities at 63 $\mu$m toward Sgr A. Shown as circles are [O I] line intensities (*top*, an average between peak and integrated line intensities), continuum intensities (*middle*), and their ratio (*bottom*), normalized by their value at the center. Shown on the left are cuts along the galactic plane, in units of 40″ offsets from the zero position. On the right are cuts perpendicular to the plane. The (0, 0) position is: R.A. = 17ʰ42ᵐ29ˢ, decl. = −28°59′ (1950). The beam size is 44″ FWHM and 60″ equivalent disk, and is shown in the middle inset. Also shown by dashed lines in the middle part of the figure are cuts of the 55 $\mu$m continuum intensities by Rieke, Telesco, and Harper (1978, corrected to the new absolute position by Becklin, Gatley and Werner 1982) at a resolution of 30″. At this resolution, the dust continuum emission has a "hole" at the position of the galactic center.

higher (30″) angular resolution (Harvey, Campbell, and Hoffman 1976; Rieke, Telesco, and Harper 1978; Becklin, Gatley, and Werner 1982 [BGW]). At this resolution, the dust emission is double-lobed and has a hole at a position near our (0, 0) position. The 63 $\mu$m [O I] emission is extended over more than 4′ (12 pc at a distance of 10 kpc) along, and 2′.6 (8 pc) perpendicular to the plane. The angular distribution of the line emission is similar to that of the dust emission at $\lambda \geq 50$ $\mu$m. The ratio of line to continuum intensity (Fig. 2, *bottom*) is approximately constant ($\sim 2.5 \pm 0.5$) at all positions, to within our measurement uncertainties of $\sim 30\%$. It is therefore an interesting question whether under slightly higher angular resolution the [O I] source would show a hole of diameter $\sim 40''$ centered on the galactic center position, similar to the dust emitting $\lambda \geq 50$ $\mu$m (Fig. 2, *middle*). The 63 $\mu$m line emission and continuum emission are distributed quite symmetrically around the galactic plane and the position of Sgr A West. The [O I] distribution is different from the angular distribution of the ionized gas (Brown and Johnson 1983). The free-free radio continuum emission and the 12.8 $\mu$m line emission from Ne II show a cluster (diameter $\sim 20''$) of compact ionized clouds surrounded by a weaker "halo" (size $\sim 40''$–$80''$) (Ekers *et al* 1975; Lacy *et al.* 1979; 1980; Brown, Johnston, and Lo 1981).

### b) Rotation Curve and Mass in the Central 10 Parsecs

The [O I] lines are spectrally resolved at all positions, and the average observed line width (FWHM) is about 300 km s$^{-1}$, well in excess of the instrumental resolution of 150 km s$^{-1}$. The line center velocities change systematically along the plane, with blueshifted velocity centroids ($v_{LSR} = -70 \pm 15$ km s$^{-1}$) at negative galactic longitudes, and redshifted centroids ($v_{LSR} = +70 \pm 15$ km s$^{-1}$) at positive galactic longitudes. The center velocities of the profiles along a line perpendicular to the plane and crossing it $\sim 20''$ north of the center are also slightly redshifted ($v_{LSR} = +10$ to $+40$ km s$^{-1}$). The data indicate a rapid transition in the *sign* of the velocities over a distance of less than 40″. The velocities cross $v_{LSR} \sim 0$ km s$^{-1}$ about 15″ south of our nominal (0, 0) position, that is, close to the true position of the galactic center as determined from the comparison of our continuum strengths with the data of Gatley *et al.* (1978). This observed rapid change of velocities around the center position and the approximately constant value away from the center indicate that the neutral oxygen gas is distributed close to the center, at radii $R \geq 1$ pc, and is rotating around the center.

The [O I] profiles may be used to determine a rotation curve and the mass of the central 1–6 pc of the Galaxy. If the gas at radius $R$ is in bound orbits at a rotational velocity $v_{orb}$, the mass internal to that radius is given by:

$$M = \frac{R v_{orb}^2}{G}, \tag{1}$$

where $G$ is the gravitational constant. The orbital velocity may be estimated from the [O I] data in two ways. First, the ratio of orbital velocity to line-of-sight radial velocity centroid $\langle v \rangle$ can be calculated if the [O I] emission is optically thin. Assuming a rotating disk of inner radius $R_i$ and outer radius $R_o$, and that the rotational velocity and volume emissivity of the 63 $\mu$m line are approximately constant between $R_i \approx 20''$ (our resolution limit) and $R_o \approx 120''$, the ratio of $v_{orb}$ to $\langle v \rangle$ at projected distance $p$ from the center is approximated by:

$$v_{orb}/\langle v \rangle = A/(1 + p/R_o), \tag{2}$$

where $A \sim 2$. If the volume emissivity decreases with radius, the constant $A$ is somewhat smaller than 2 ($\sim 1.7$–$1.9$ if emissivity decreases as $R^{-2}$, for example). Since $\langle v \rangle = 70 \pm 10$ km s$^{-1}$, the orbital velocity in this model at $R = 20''$ is $120 \pm 20$ km s$^{-1}$. The value would not change much if there are noncircular motions in addition to pure rotation, as long as these motions only symmetrically broaden the line profile.

A second estimate of $v_{orb}$ may be obtained from the line widths if the virial theorem applies. The observed average widths (200–400 km s$^{-1}$) of the [O I] profiles correspond to an average intrinsic width (FWHM) of $\Delta v = 150$ km s$^{-1}$ if the lines are intrinsically Lorentzian in shape. In the other extreme of an intrinsic rectangular line shape, the observed width corresponds to $\Delta v = 250$ km s$^{-1}$. A Gaussian line shape would result in a width in between these two extreme cases. If the line broadening is due to the motions of a collection of clouds in randomly oriented, bound orbits, $v_{orb} = \sqrt{3}\,\sigma$, where $\sigma$ is the line-of-sight velocity dispersion. For a rectangular profile $\sigma = 0.3\Delta v$ and for a Gaussian $\sigma = 0.4\Delta v$ ($\sigma$ is not defined for a Lorentzian). The observed average width then corresponds to a velocity dispersion of 80 km s$^{-1}$ and an orbital velocity of 140 km s$^{-1}$, approximately independent of the shape of the lines. This second estimate of the rotational velocity is consistent with the first estimate. An orbital velocity of 100–140 km s$^{-1}$ implies a mass of $2$–$5 \times 10^6$ $M_\odot$ within 1 pc of the galactic center. The approximately constant velocity centroids and the constant or increasing velocity dispersion away from the center suggest that the mass is increasing approximately proportional to radius at $R > 1$ pc. Thus the mass within 5 pc of the galactic center may be $\sim 2 \times 10^7 M_\odot$. The approximately constant value of the central velocity in the spectra above and below the galactic plane indicates that the [O I] gas rotates around the center with an axis close to that of the general galactic rotation. This is also supported by the maps of BGW which show that the major axis of the far-infrared dust distribution is coincident with the galactic plane to within 10°.

### c) *Noncircular Motions?*

While the data clearly show general rotation, there are also indications of noncircular motions. First, the velocity widths appear to be largest at the positions farthest away from the central position, contrary to what is expected for a ring or torus of rotating gas with constant rotational velocity. Second, two spectra at *negative* longitudes ($\Delta l = -80''$ and $\Delta l = -120''$) show gas at *positive* velocities which is strictly "forbidden" for pure rotation. While the quality of the spectra is not sufficient to draw more detailed conclusions, these indicate that the magnitude of the noncircular motions (e.g., expansion, infall, or turbulence) may be comparable to the rotational motion.

### d) *Comparison with Other Observations*

The fine structure line emission of [Ne II] at 12.8 $\mu$m averaged over the central 2 pc has a width (FWHM) of $\sim$200 km s$^{-1}$ (Wollman *et al.* 1977). The [Ne II] emission predominantly arises from compact ($\theta \lesssim 5''$), dense ($n_e \approx 10^5$ cm$^{-3}$) clouds in the central 1 pc of the Galaxy (Lacy *et al.* 1979, 1980). The center velocities of the ionized clouds are consistent with rotation, although the derived rotational axis may be different from the rotation axis of the Galaxy at large (Lacy *et al.* 1980). Most of the Ne II clouds are concentrated within the central 15″ of the center, but there are two condensations 30″ north and south of the center, approximately along the galactic plane. Their LSR velocities are +110 and −120 km s$^{-1}$, respectively, and are consistent with the rotation velocities obtained from the [O I] data at that radius. The distribution of velocities of 14 Ne II clouds is best fit by a mass distribution containing a central point mass [$M(R) = 3 \times 10^6 R_{pc} + 3 \times 10^6 M_\odot$, where $R_{pc}$ is radius in pc], but a solution without a central point mass [$M(R) = 1.2 \times 10^7 R_{pc}$] is also possible at a confidence limit 1.4 $\sigma$ below the first solution (Lacy *et al.* 1980). The solution with a central point mass is in better agreement with our data, since it requires only $6 \times 10^6 M_\odot$ for the mass within 1 pc of the center. This is larger than, but close to, our value of 2–$5 \times 10^6 M_\odot$. The higher mass derived from the [Ne II] data results from the high observed rms velocity of the clouds very close to the center. The rms velocity given by Lacy *et al.*, assuming random orbits, is 220 km s$^{-1}$. The apparent increase of the velocities within 10″ of the galactic center may be associated with a large point mass, or may be caused by noncircular motions (e.g., infall) or by a nonaxisymmetric gravitational field (e.g., a bar). Calculations of the dynamics of triaxial stellar systems by Schwarzschild (1979) and Merritt (1980) show a strong increase of the line-of-sight velocity dispersion toward the center of the stellar cluster due to the highly aspherical orbits.

Radio observations of the atomic and molecular gas in the vicinity of the galactic center also show a component of velocity range $\sim$300 km s$^{-1}$ (cf. Scoville 1972; Bania 1977; Liszt and Burton 1978; Güsten and Downes 1980; Whiteoak, Gardner, and Pankonin 1983). These data show that this high-velocity gas, however, is probably part of a large scale (diameter greater than several hundred pc) rotating and expanding ring, bar, or disk and is not directly associated with the galactic center. Unfortunately, the emission from this "expanding ring" and other clouds at different velocities, and thus different distances from the center, make it difficult to identify a counterpart of the high-velocity [O I] source in the radio spectra. High-resolution, interferometric observations may soon change this situation.

### e) [O III] *Emission*

We observed the 88 $\mu$m $^3P_1$–$^3P_0$ fine structure line of [O III] at the position of the galactic center (R.A. = $17^h42^m29^s$, decl. = −28°59′20″ [1950]). The line has an integrated intensity of $(7 \pm 2) \times 10^{-18}$ W cm$^{-2}$. This is consistent with the detection reported by Dain *et al.* (1978) in a much larger beam (4′ × 4′.4) around Sgr A only if much of the [O III] detected in the larger beam comes from distances greater than 1 pc from the galactic center. Previously, Watson *et al.* (1980) had detected the second $^3P_2$–$^3P_1$ line of the $O^{++}$ ground state triplet at 52 $\mu$m, with an intensity of $(5.2 \pm 2)\, 10^{-17}$ W cm$^{-2}$ in a 1′ beam. The low intensity of the 88 $\mu$m line indicates that the [O III]-emitting gas along the line of sight to the galactic center has a high density. From the ratio of the 88 to 52 $\mu$m line intensity ($0.13 \pm 0.05$) it is clear that the density is high enough to collisionally saturate both lines (see derivations in Storey, Watson, and Townes 1979, and Watson *et al.* 1980). The measurement uncertainties allow any density greater than $6 \times 10^3$ cm$^{-2}$. Here we have assumed that the $O^{++}$ triplet is collisionally populated by electron impact at an electron temperature of 5000 K, which is probably appropriate for the galactic center region (Rodriguez and Chaisson 1979; Pauls 1980). The derived density, however, is only weakly dependent on the choice of electron temperature. As discussed by Watson *et al.* (1980), any additional component of widely distributed [O III] gas must then have a density $\lesssim$40 cm$^{-3}$.

## IV. DISCUSSION

### a) *Excitation of the* [O I] *Line: General Constraints*

Radiative excitation is a negligible source of excitation of the [O I] line. Resonant scattering of 63 $\mu$m photons emitted by the coextensive dust cannot produce a line which is about twice as bright as the 63 $\mu$m continuum. Pumping mechanisms are also inadequate. The total emission rate of 63 $\mu$m photons integrated over the [O I] source is $\sim 10^{52}$ s$^{-1}$, which exceeds the Lyman continuum photon luminosity ($\sim 10^{51}$ s$^{-1}$). Therefore, pumping by these photons to ionized or electronically excited states followed by recombination and/or cascade through the 63 $\mu$m transition fails by at least an order of magnitude to explain the observed [O I] 63 $\mu$m luminosity.

Collisional excitation by neutral atomic hydrogen impact is the most likely excitation mechanisms. As pointed out by Lester *et al.* (1981), the [O I] emission can only come from partially ionized ($n_e/n_H \sim 0.1$) or neutral gas, since the ionization potential of oxygen is only slightly greater than that of hydrogen (13.618 vs. 13.593 eV). In predominantly neutral gas, the collisional excitation of the neutral oxygen triplet will be dominated by neutral hydrogen impact, since the collision strengths for neutral atomic hydrogen impact are only a factor of 5 lower than those for excitation by electrons and protons (Saraph 1973; Le Dourneuf and Nesbet 1976; Launay and Roueff 1977).

Because the excitation is collisional, constraints can be derived on the atomic hydrogen density $n_H$, the mass of neutral atomic gas $M_H$, and the average temperature $T$ in the atomic region from the observed line and continuum intensity and extent. By equating the intensities of the line and continuum to blackbody intensities (assuming a beam filling factor of unity), we obtain a lower limit for the optically thick case, to the gas temperature of $T \gtrsim 40$ K and to the grain temperature of $T_{gr} \gtrsim 35$ K.

However, it is extremely unlikely that either the warm dust or the [O I] is optically thick at 63 $\mu$m. First, infrared continuum observations show that the dust temperature decreases with distance from the galactic center, suggestive of a central, hot heating source which BGW identified with the ultraviolet sources which ionize Sgr A West. Naively, one would then expect that the size of the far-infrared dust emitting region corresponds to the penetration depth of the ultraviolet radiation from the center ($A_v \sim 1$–5). Therefore, the optical depth of the emitting dust at 63 $\mu$m is $\tau_D$ (63 $\mu$m) $\sim 1$–$5 \times 10^{-2}$, assuming grain extinction varies as $\lambda^{-1}$ so that $A_v \sim 10^2 \tau_D$ (63 $\mu$m). This simple argument is supported by the observations: BGW and Rieke, Telesco, and Harper (1978) derive a peak optical depth of the warm dust emission at 63 $\mu$m over the central 10 pc of $\tau_D$ (63 $\mu$m) $\sim 0.05$–0.08. Furthermore, one would expect the O I to be coextensive with the warm dust, since the ultraviolet flux also maintains the atomic gas by dissociating molecules. This, too, is borne out by observations: the constant line to continuum ratio suggests that the O I gas is coexistent with warm dust outside the ionized region Sgr A West. If the solar neighborhood gas-to-dust ratio applies, $N_H \sim 2 \times 10^{23} \tau_D$ (63 $\mu$m) (Savage and Mathis 1979), the column density of atomic gas $N_H$ in the O I region must be of order $10^{21}$–$10^{22}$ cm$^{-2}$ to produce $A_v \sim$ several. The line center optical depth $\tau_L$ of the 63 $\mu$m line can be estimated from

$$\tau_L = 0.16 \times \left(\frac{\chi_O}{6.6 \times 10^{-4}}\right)\left(\frac{N_H}{10^{22}\ \text{cm}^{-2}}\right) \qquad (3)$$
$$= 3.2\left(\frac{\chi_O}{6.6 \times 10^{-4}}\right) \times \tau_D\ (63\ \mu\text{m}) ,$$

where $\chi_O$ is the fractional abundance of oxygen relative to hydrogen. We have assumed that the line is a Lorentzian, has a full width at half-maximum of 150 km s$^{-1}$, that all the O is O I, and that the dust-to-gas ratio is similar to that in the solar neighborhood. A hydrogen column density of $\sim 10^{22}$ cm$^{-2}$ implies a line opacity of 0.1; a size of $12 \times 3$ pc indicates a total mass of atomic gas of $\sim 2 \times 10^3\ M_\odot$ and an average hydrogen density of $\sim 500$ cm$^{-3}$ in the [O I] emitting region.

Therefore, we assume that the [O I] and warm dust are coextensive and optically thin at 63 $\mu$m and we use the observed line and continuum intensities to constrain $T$ and $n_H$. In the calculations below we use as an upper limit to $T_{gr}$ the dust color temperatures in this region which lie between 60 K and 90 K (BGW). We treat both the low-density and high-density limits for optically thin [O I] emission.

Peak line intensities $I_L$ (above the continuum) and dust continuum intensities $I_C$ at frequency $\nu$ in the optically thin limit are given by

$$I_L = \frac{2h\nu^3}{c^2}\left(\frac{g(J=1)n_O(J=2)}{g(J=2)n_O(J=1)} - 1\right)^{-1} \tau_L , \qquad (4)$$
$$I_C = \frac{2h\nu^3}{c^2}\left[\exp\left(\frac{228}{T_{gr}}\right) - 1\right]^{-1} \tau_d ,$$

where $g(J=1) = 3$, $g(J=2) = 5$, and $n_O(J=1)$, $n_O(J=2)$ are the statistical weights and population densities in the upper ($J=1$) and lower ($J=2$) O I fine structure levels, respectively. The critical density for collisional dexcitation of the [O I] 63 $\mu$m transition by atomic hydrogen is $n_{cr} \approx 4.8 \times 10^8/T$, where $T$ is the gas temperature in Kelvins (Launay and Roueff 1977). For $n_H \ll n_{cr}$, the population in the $J=2$ level is about equal to the total density of neutral oxygen $n_O$(tot), and the line-to-continuum ratio is

$$\frac{I_L}{I_C} = \frac{5}{3}\frac{n_O(J=1)}{n_O(\text{tot})}\frac{\tau_L[\exp(228/T_{gr}) - 1]}{\tau_d} . \qquad (5)$$

Taking the observed $I_L/I_C = 2.5$ and $T_{gr} = 60$ K, we obtain

$$\frac{n_O(J=1)}{n_O(\text{tot})} = \frac{\gamma_{21}(T)n_H}{A_{12}} = \frac{n_H}{n_{cr}} = 1\text{–}4 \times 10^{-2}\left(\frac{6.6 \times 10^{-4}}{\chi_O}\right) , \qquad (6)$$

where $\gamma_{21}$ ($T$) (cm$^{+3}$ s$^{-1}$) is the collisional rate coefficient for a transition from a lower ($J=2$) to an upper ($J=1$) state and $A_{12} = 8.95 \times 10^{-5}$ s$^{-1}$ is the Einstein coefficient. This fractional population in $J=1$ can be calculated in the low-density limit for a range of densities and temperatures, and we find

$$n_H T = 10^{7 \pm 0.2} [\text{cm}^{-3}\ \text{K}] . \qquad (7)$$

This expression is a good approximation in the region $T \geq 100$ K and $n_H \lesssim 10^6$ cm$^{-3}$. Hence, the possible range of parameters includes a warm, dense, and clumpy medium with $n_H = 3 \times 10^5$ cm$^{-3}$ and $T = 100$ K and hot, evenly distributed gas with $n_H = 10^3$ cm$^{-3}$ and $T$ is a few times $10^3$ K. In all of these cases, the gas is warmer than the dust. We note that in the low-density limit at fixed temperature, $I_L/I_C \propto n_H$, so that isothermal clumping might be expected to produce variations in the line-to-continuum ratio across the source. However, the observations show approximately constant $I_L/I_C$. The above results show that isobaric clumping (with $n_H T \sim$ const) could produce the observed homogeneity in $I_L/I_C$.

In the high-density limit $n \gg n_{cr}$, the line-to-continuum ratio is independent of $n$ and given by

$$\frac{I_L}{I_C} = \frac{\tau_L}{\tau_D}\frac{(e^{228/T_{gr}} - 1)}{(e^{228/T} - 1)} . \qquad (8)$$

With $I_L/I_C = 2.5$ and $T_{gr} = 60$–90 K as above, we find $T = 70$ K. In summary then, the general (relatively model-independent) constraints on $n$, $T$, and $T_{gr}$ from the observed line and continuum observations are that 35 K $< T_{gr} <$ 90 K, $T \gtrsim 70$ K, and $n_H T \approx 10^7$ cm$^{-3}$ K. In the next section we discuss heating and cooling mechanisms and propose that

$n_H \gtrsim 10^5$ cm$^{-3}$ and $T \sim 100$–300 K may be the most likely choice of parameters.

### *b) Heating and Cooling of the Gas*

In the following, we will assume that the dust at radii of 1–6 pc from the center is heated directly by the source or sources in the central parsec which ionize the clouds in Sgr A West (BGW). The absorption scale length for UV radiation heating must then be of the order of a few parsecs, and the average atomic hydrogen column density through the central few parsecs is $10^{21}$–$10^{22}$ cm$^{-2}$. Note, however, that an extended cluster of ionizing sources with a $1/R^2$ density distribution could result in the dust temperature gradient observed by BGW and would be consistent with the extended radio free-free emission around Sgr A West. In this case, hydrogen column densities through the central few parsecs may exceed $10^{22}$ cm$^{-2}$ and the local ultraviolet radiation field may be larger than estimated below. Independent of the distribution of the UV radiation, however, the heating mechanism in the atomic gas must be quite efficient. The total luminosity in the [O I] 63 $\mu$m line ($\sim 10^5$ $L_\odot$) is about 1% of the observed bolometric luminosity absorbed by grains in this region, $\sim 10^7$ $L_\odot$, and reradiated in the far-infrared. The cooling in this line is likely to equal the total gas cooling (and therefore heating) since [O I] 63 $\mu$m emission dominates the cooling of atomic gas at $n_H \gtrsim 10^4$ cm$^{-3}$ and $T \geq 100$ K. Therefore, after considering shock excitation, we discuss two mechanisms which may convert about $\epsilon \sim 0.01$ of the visible/UV radiation into gas heating. Grain-gas collisions are probably unimportant since that mechanism will contribute significantly to the gas heating in Sgr A only at hydrogen density greater than $10^6$ cm$^{-3}$, higher than is most likely present in the galactic center. Using the standard interstellar value for the gas to dust ratio (Savage and Mathis 1979) and the effective grain-gas collision cross sections listed by Hollenbach and McKee (1979), grain-gas collisions fail by at least one order of magnitude at a density of $10^5$ cm$^{-3}$, and more at lower densities ($\propto n_H^2$) to account for the [O I] luminosity (assuming that the 63 $\mu$m line carries *all* of the gas cooling).

#### i) *Shock Heating*

The broad 63 $\mu$m lines are indicative of supersonic gas motions and suggest that shock waves with speeds of $\gtrsim 100$ km s$^{-1}$ could be responsible for the [O I] emission. Evidence for the presence of shock-heated gas comes from the detection of 2 $\mu$m quadrupole emission of hot molecular hydrogen in this region (I. Gatley, private communication). However, high-velocity shocks radiate only about 1% of the shock energy in the [O I] 63 $\mu$m line (Hollenbach and McKee 1979). Therefore, a total shock energy dissipation of $\sim 10^7$ $L_\odot$ is required to produce the observed [O I] emission, and a kinetic energy input at this rate is necessary. This is, for example, $\sim 10^4$ times more than the kinetic energy available from the ionized clouds in Sgr A West discussed by Lacy *et al.* (1980). If the kinetic energy input is due to mass loss from a single driving source at the galactic center, the [O I] data imply a mass loss rate of 1–10 $M_\odot$ yr$^{-1}$. The volume emission measure of such a wind, if ionized, would be several orders above the limits set by Brackett line or VLA observations. Furthermore, the total mass loss from the early type stars required to provide the observed ionizing luminosity in the central 3 pc would probably not exceed $10^{-4}$ $M_\odot$ yr$^{-1}$ (Hutchings 1976; Lacy, Townes, and Hollenbach 1982). Hence, shock excitation due to mass loss is unlikely to cause the [O I] emission.

Alternatively, the kinetic energy input for shock excitation could come from dissipation of noncircular motions due to a non-axisymmetric perturbation of the gravitational field, such as a triaxial density distribution of the central stellar cluster.

#### ii) *Ultraviolet Excitation of* $H_2$

$H_2$ molecules forming in the [O I] atomic region are rapidly destroyed by absorption of 11–13.6 eV photons which electronically excite the molecules followed by a radiative transition to the vibrational continuum of the ground state. For every $H_2$ dissociation, however, there are roughly nine transitions to bound vibrational states, typically with vibrational energy $E_v \sim 2.2$ eV (cf. Hollenbach and McKee 1979). This vibrational energy is available to heat the gas if $n_H$ and $T$ are sufficiently high that collisional deexcitation proceeds prior to radiative cascade down the vibrational ladder. The critical density $n_{cr}^{H_2}$ for collisional deexcitation is approximately

$$n_{cr}^{H_2} = 6 \times 10^5 T^{-1/2} \exp [(400/T)^2] \text{ cm}^{-3} . \qquad (9)$$

The rapid rise in $n_{cr}^{H_2}$ for $T \lesssim 300$ K indicates that $n_H \gtrsim 10^5$ cm$^{-3}$, $T \gtrsim 300$ K are required for the ultraviolet pumping of $H_2$ to be a significant heat source in the galactic center.

Assuming that $H_2$ formation proceeds (Hollenbach and McKee 1979) at the elevated grain and gas temperatures relative to this region, the efficiency of gas heating can be written for $n_H > 10^5$ cm$^{-3}$ and $T \gtrsim 300$ K as

$$\epsilon = H_{UV}/F_{bol} , \qquad (10)$$

where

$$H_{UV} = 9E_v \int_0^{N_{cr}} \frac{\beta I}{N_2^{1/2}} dN_2$$

is the columnar rate of heat deposition, $N_2$ is the column density of $H_2$, $I$ is the unattenuated ultraviolet destruction rate of $H_2$, $\beta = 4.2 \times 10^5$ cm$^{-1}$, $N_{cr} \sim 10^{21}$ cm$^{-2}$ is the column density where grain attenuation rapidly diminishes the ultraviolet field, and $F_{bol}$ is the bolometric flux incident on the gas (cf. Jura 1974). Since $I \propto F_{bol}$, the result is independent of the ultraviolet flux and is approximately $\epsilon \approx 8 \times 10^{-3}$ for $n_H \gtrsim 10^5$ cm$^{-3}$ and $T \gtrsim 300$ K.

If $n_H \lesssim n_{cr}^{H_2}$, the ultraviolet pumping leads to 2 $\mu$m emission as discussed by Hollenbach and Shull (1977). We have shown above that ultraviolet excitations results in $\sim 8 \times 10^{-3}$ of the bolometric luminosity $L_{bol}$ incident upon the region being converted to vibrational excitation of $H_2$. In the limit of no collisional redistribution between vibrational states, about 2% of the ultraviolet excitations result in the emission of a 1–0 $S(1)$ photon, and for each molecule which cascades through 1–0 $S(1)$ only $\sim 0.25E_v$ emerges in this transition. This gives

$$L[S(1)] \sim 4 \times 10^{-5} L_{bol} . \qquad (11)$$

In the galactic center, therefore, assuming that $n_H < n_{cr}^{H_2}$ and that $L_{bol} \sim 5 \times 10^6$ $L_\odot$ is incident upon the neutral gas, approximately 200 $L_\odot$ emerges in the 1–0 $S(1)$ line. This corresponds to an unattenuated surface brightness of $\sim 2 \times 10^{-4}$ erg cm$^{-2}$ s$^{-1}$ sr$^{-1}$, or an observed surface brightness of $\sim 3 \times 10^{-5}$ ergs cm$^{-2}$ s$^{-1}$ sr$^{-1}$. This within a factor of 2 of the $S(1)$ surface brightness observed by Gatley (private communication) toward the dust lobes ($7.4 \times 10^{-5}$ ergs cm$^{-2}$ s$^{-1}$ sr$^{-1}$).

Collisional redistribution of vibrationally excited $H_2$ alters this result in two ways. For $n > n_{cr}$, the vibrational energy is channeled into heat and the 1–0 $S(1)$ flux is reduced by $\sim n_{cr}/n$. For densities $n \lesssim n_{cr}$, resonant vibrational transfers [e.g., $H_2$ $(v = 2) + H_2$ $(v = 0) \rightarrow H_2$ $(v = 1) + H_2$ $(v = 1)$] may enhance the 1–0 $S(1)$ flux (see discussion in Hollenbach and Shull 1977).

iii) *Photoelectric Heating*

The flux of 6–13.6 eV photons incident upon dust grains leads to photoejection of electrons from grain surfaces into the gas, a process which can heat the gas. Tielens and Hollenbach (1983), using the previous results of de Jong (1977, 1980) and Draine (1978), discuss in detail this mechanism in atomic regions illuminated by strong ultraviolet fluxes. The heating efficiency $\epsilon$ depends on $\chi^{-1}T^{-1/2}n_e$, where $\chi \approx 3 \times 10^4 L_{41}\, d_{19}{}^{-2}$ is proportional to the ultraviolet flux and $n_e$ is the electron density. $L_{41}$ is the bolometric luminosity in units of $10^{41}$ ergs s$^{-1}$ and $d_{19}$ the distance from the central source in $10^{19}$ cm. The efficiency is inversely proportional to $\chi T^{1/2} n_e{}^{-1}$, since greater ultraviolet flux and/or lower electron densities lead to positive charging of the grain, which retards the electron energy input.

Neutral grains result in $\epsilon \sim 2 \times 10^{-2}$ in the galactic center, a result which can be understood by noting that $L_{UV}/L_{bol} \sim 0.5$, that the photoelectric yield is $\sim 0.1$, and that the work function of grain material is $\sim 6$ eV so that only $\sim 0.4$ of the effective photon energy is released as heat. Grains attain significant positive charge at $\chi T^{1/2} n_e{}^{-1} \approx 10^4$, where $\epsilon \sim 3 \times 10^{-3}$, and the heating efficiency drops rapidly for $\chi T^{1/2} n_e{}^{-1} > 10^4$ ($T$ in K, $n_e$ in cm$^{-3}$). Since $\chi \sim 3 \times 10^4$ in the galactic center, an efficiency $\epsilon > 3 \times 10^{-3}$ requires that

$$n_e \gtrsim 30(T/100)^{1/2}\ \mathrm{cm}^{-3}\ , \qquad (12)$$

or

$$n_H \gtrsim 10^5(T/100)^{1/2}\ \mathrm{cm}^{-3}\ ,$$

assuming that all carbon is $C^+$ in the [O I] region and that $C^+$ is the principal source of electrons. This result is independent of the dust-to-gas mass ratio, since the calculated efficiency is the heat delivered to the gas divided by the radiation absorbed per grain. Therefore, photoelectric heating is a promising mechanism for producing the observed [O I] emission if $n_H \gtrsim 10^5$ cm$^{-3}$.

In summary, ultraviolet pumping of $H_2$ molecules followed by collisional deexcitation of vibrationally excited $H_2$ photoelectric heating of the gas are viable mechanisms for converting $\sim 10^{-2}$ of the absorbed radiation into gas heating. Both mechanisms require $n_H \gtrsim 10^5$ cm$^{-3}$, the first in order that collisional deexcitation is operant and the second in order that electrons keep the positive charge of the grains suppressed. In both cases the gas temperature has to be 100–300 K, and exceeds the grain temperature. Alternatively, the [O I] gas may be heated by dissipation of noncircular motions. However, the conversion of ultraviolet luminosity to atomic gas heating with an efficiency $\epsilon \sim 10^{-3}$ to $10^{-2}$ is apparently a general phenomenon applicable to extensive regions such as M42 and M17, where shock dissipation cannot apply (Tielens and Hollenbach 1983). We therefore favor the ultraviolet-initiated mechanisms over shock dissipation. Shock heating of the [O I] region due to mass loss from the galactic center probably can be excluded. We also note that heating by low-energy cosmic rays at a rate of $10^{-17}$ s$^{-1}$ per hydrogen atom fails by at least five orders of magnitude to account for the observed [O I] luminosity.

*c) Composition of the Gas*

Tielens and Hollenbach (1983) give a detailed treatment of the chemistry of photodissociated atomic regions near sources of large UV fluxes. Their results are generally similar to previous work (Glassgold and Langer 1974; Black and Dalgarno 1977; Barsuhn and Walmsley 1977; de Jong, Dalgarno, and Boland 1980) which treated atomic regions illuminated by the ambient interstellar UV field. However, the large ultraviolet fluxes near H II regions maintain larger column densities of photodissociated gas. When $n_H \lesssim 10^5$ cm$^{-3}$, hydrogen becomes molecular at $N_H \sim 10^{21}$–$10^{22}$ cm$^{-2}$ where grains attenuate the UV field. For $n_H > 10^5$ cm$^{-3}$, $H_2$ self-shielding leads to smaller column densities required for conversion of H to $H_2$. However, oxygen and carbon are primarily in O I and C II until $N_H \sim 10^{21}$ cm$^{-2}$, since photodestruction of OH, $H_2O$, $O_2$, and CO is appreciable until grain attentuation of the radiation field commences. At column densities greater than a few times $10^{21}$ cm$^{-2}$ the fractional abundance of molecular material is rapidly increasing. Hence, the [O I] emission in the galactic center most likely originates in gas with mixed atomic and molecular composition, with the atomic fraction increasing toward the center of the Galaxy and dominating at the surfaces of clumps exposed to the strong UV radiation field. At densities of $n_H \geq 10^4$ cm$^{-3}$ and temperatures $T \geq 100$ K, the [O I] 63 $\mu$m line dominates the atomic cooling. [C II] 158 $\mu$m cooling may dominate at somewhat lower densities and temperatures.

*d)* [O III] *and the Radio "Halo"*

The derived density for the $O^{++}$-containing plasma of $n_e \gtrsim 6 \times 10^3$ cm$^{-3}$ is significantly higher than $n_e \sim 600$ cm$^{-3}$, the density estimated for the extended ($\theta \gtrsim 40''$) "halo" of radio continuum emission in Sgr A West (Rodriguez and Chaisson 1979; Ekers *et al.* 1975; Brown, Johnston, and Lo 1981). The value is, however, consistent with the electron density deduced for the compact ionized clouds from the [Ne II] line and the radio continuum measurements ($n_e \sim 10^5$ cm$^{-3}$; Lacy *et al.* 1980; Brown, Johnston, and Lo 1981). Since the 88 $\mu$m [O III] line should be quite intense from an extended halo with average densities $n_e \sim 600$ cm$^{-3}$, the radio emission from the halo may be nonthermal, or the electrons of the halo may be clumped in many dense, compact clouds of density $n_e \gg 10^3$ cm$^{-3}$ which appear as an extended background in the radio measurements (see the discussion in Watson *et al.* 1980). Alternatively, but less likely, the fractional population of oxygen in the second ionization state may be extraordinarily low in the halo ($n_{O^{++}}/n_O < 10^{-2}$). Such a low degree of ionization may be caused by a radiation field of low effective temperature. Assuming a total number of Lyman continuum photons in the central few parsecs of 4–8 $\times 10^{50}$ s$^{-1}$ (Mezger and Pauls 1979; Lacy *et al.* 1980), an effective temperature as low as $\sim 27{,}000$ K would be required to explain the lack of [O III] 88 $\mu$m emission from a medium-density halo. This value is significantly lower than that derived for the compact plasma clouds from the near-infrared fine structure lines ($T_{\rm eff} \leq 35{,}000$ K, Lacy *et al.* 1980). The 2 $\mu$m emission from such a soft radiation field would also be too bright to be consistent with the observations (Lacy, Townes, and Hollenbach 1982). Hence, the radiation field would have to be softened somewhere between the clouds and the halo. A large amount of He, for example, confined to the immediate vicinity of the [Ne II] clouds, could provide such filtering. However, a comparison of the observed emission measures in the radio and infrared with the far-infrared luminosity integrated over the inner $\sim$10 pc suggests that the central core of the H II region Sgr A West is not ionization bounded (Lacy *et al.* 1980; BGW). Only about 30%–50% of the ionizing photons may actually be absorbed within the ionized clouds. This can be derived from the low geometrical "blocking" or "filling" of the compact plasma clouds. It is therefore unlikely that there is enough H or He outside the plasma clouds to significantly change the effective temperature of the radiation field present within the clouds. It is possible that most of the halo gas actually is arranged as ionized "rims" at the boundaries to the neutral gas condensations farther out where the far-infrared dust emission and [O I] line arise. The high densities indicated by the [O III] data are then consistent with the densities of $\gtrsim 10^5$ cm$^{-3}$ estimated above for the neutral gas.

## IV. CONCLUSIONS

This paper presents measurements of the distribution of 63 $\mu$m emission from neutral oxygen over the central 10 pc of the Galaxy, as well as a determination of the flux in the 88 $\mu$m line from doubly ionized oxygen toward Sgr A West. The principal conclusions are the following:

1. The [O I] emission is extended along the galactic plane. A systematic variation of line center velocity with position shows that the emitting gas rotates around the galactic center with an axis close to that of the general galactic rotation.

2. The velocity field shows that the mass within 1 pc of the galactic center is $\sim 3 \times 10^6\ M_\odot$; the enclosed mass increases linearly with radius out to 5 pc from the center. The velocities found are less than those of the ionized clouds within $\frac{1}{2}$ pc of the center, and hence are probably not consistent with a steady-state spherical cluster of stars. The [O I] lines have line widths up to a few hundred km s$^{-1}$, suggesting considerable turbulent or noncircular motion, in addition to rotation.

3. The total luminosity radiated in the [O II] 63 $\mu$m line over the region studied in $10^5\ L_\odot$, which is $\sim$1% of the total observed luminosity of the region.

4. The gas radiating the [O I] line is probably heated by the ultraviolet sources in the galactic center, through an indirect process involving either photoejection from grains or collisional deexcitation of radiatively excited $H_2$. For either mechanism to work with the required efficiency, a density of $\gtrsim 10^5$ hydrogen atoms cm$^{-3}$ is required in the region of [O I] emission. For this density, the temperature of the gas is estimated to lie between 100 and 300 K. However, excitation of the O I gas by the dissipation of noncircular motions may also be possible.

5. The total mass of warm, neutral, atomic gas in the central 10 pc of the Galaxy is $\sim$2000 $M_\odot$. For densities $10^5$ cm$^{-5}$, the gas is highly clumped and fills only a few percent of the volume.

6. The relative intensities of the 88 $\mu$m and the (previously measured) 52 $\mu$m lines of O III suggests that the electron density in the region of O III emission exceeds $10^4$ cm$^{-3}$. No evidence is seen for the uniform, low-density halo deduced from radio observations. It is suggested that the halo gas is nonthermal or is concentrated in dense clumps or filaments, which may be ionized on rims on the neutral clumps seen in the [O I] 63 $\mu$m line.

This research was supported by NASA grant NGR 05-003-511 for airborne astronomy. We are grateful to the staff of the Kuiper Airborne Observatory for their excellent support. Thanks are also due to K. Evenson for helpful discussions and I. Gatley for communicating data prior to publication.

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