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STELLAR VELOCITIES AND THE MASS DISTRIBUTION IN THE GALACTIC CENTER

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ABSTRACT

Radial velocities have been measured for 43 stars within 6.5 pc of the Galactic center. The stellar velocity dispersion of ~ 75 km s^{-1} is virtually independent of radius from 0.36 pc to 6 pc, indicating that an extended mass distribution is being sampled over this entire range. The stellar velocities do not show the increase within 2 pc of Sgr A* found for the gas, suggesting that the gas motions may be affected by nongravitational forces. If the core radius of the stellar distribution is ~ 0.1 pc, these data require no unseen mass within the Galactic center; however, if the core radius is ~ 0.6 pc, an unseen mass of $\sim 2 \times 10^6$ $M_{\odot}$ may still exist.

Subject headings: galaxies: internal motions — galaxies: nuclei — galaxies: The Galaxy

I. INTRODUCTION

Measurements of gas motions in the center of the Galaxy, summarized by Genzel and Townes (1987) and supplemented since then by Serabyn *et al.* (1988), show high velocities in the central parsec and lead to the identification of a point central mass of 2.5 to 3×10^6 $M_{\odot}$. The presence of a unique compact, nonthermal radio source near the position indicated for this mass (Lo 1987 and references therein) and close to IRS 16 has produced strong support for a model in which a black hole central engine powers the central few parsecs (e.g., Gatley 1987). This model has obvious analogies with black hole models for the central engines in Seyfert galaxies and QSOs, although the hypothesized mass and the required luminosity in the Galactic center are on a much smaller scale. If the model is correct, it implies that much can be learned about powerful nonthermal extragalactic sources by the detailed studies possible at the Galactic center.

Two worries persist regarding this picture. First, it has recently been shown that no bright infrared source actually coincides with Sgr A* (Allen and Sanders 1986; Forrest *et al.* 1987; Becklin *et al.* 1987; Rieke, Rieke, and Paul 1988). Second, the gas in the Galactic center may be subject to nongravitational forces leading to high velocities, in which case the mass in the region will be overestimated. This second possibility can be tested by measuring the radial velocities of individual stars, whose motions should be controlled virtually completely by gravity (Sellgren *et al.* 1987). This *Letter* reports the results of such measurements.

II. NEW OBSERVATIONS

Spectra of the Galactic center sources at the position of the 2–1 CO band head (2.296 μm) are shown in Figure 5 of Rieke, Rieke, and Paul (1988, hereafter Paper I) and Figures 2 and 3 of Rieke and Rieke (1988, hereafter Paper III). These data were obtained with the CTIO 4 m telescope and the facility infrared spectrometer. A grating with 210 lines mm^{-1} was used with either a 2''.3 × 2''.3 or 2''.3 × 5'' slit to give a spectral resolution of 1082 (277 km s^{-1}). The grating was stepped to provide a data point every 46.2 km s^{-1}, or one-sixth of the spectral resolution. Telluric features and the instrumental response were removed from the data by ratioing them to similar measurements of a nearby solar-type star.

Spectral calibration and repeatability is central to application of these data to velocity measurements. The initial calibration for each night was by reference to a gas lamp provided with the spectrometer. During observations, the instrument tracks the grating position by keeping track of the pulses issued to the stepper motor that turns the grating. The desired wavelength is translated to a grating position as determined from the grating equation. This procedure always placed the instrumental wavelength within a fraction of a motor step of the position we requested. The data reported here were recorded at an interval of one motor step.

To derive accurate velocities, we needed to calibrate wavelengths much more accurately than this open loop procedure provided. We therefore used source 7 in the Galactic center, a very bright M1 Ia star with strong CO bands, as a wavelength calibrator. A spectrum of the CO band head of source 7 was obtained roughly every hour while we were observing in the Galactic center, and all velocity measurements were referred to it. The velocity of IRS 7 has been determined accurately in previous work. Sellgren *et al.* (1987) find -130 km s^{-1} for this star, while from the spectrum reported by Lebofsky, Rieke, and Tokunaga (1982), we find -125 km s^{-1}. In the following, a value of -128 km s^{-1} has been adopted. On a cloudy night, we tracked the behavior of the spectrometer as determined over the track of the Galactic center but viewing the calibration lamp and found that the flexure measured from IRS 7 showed larger excursions, but only by about 20 km s^{-1}. We used curves of wavelength calibration versus time for each night to interpolate the measurements for each Galactic center star to the most accurate possible velocity. From the behavior of these curves, it appears that the errors in our derived velocities are roughly 20 km s^{-1} (rms). This error estimate is supported by sources measured in common with Sellgren *et al.* (1987) and those that were repeated on different nights during our measurements.

Figure 1 shows measurements of the CO bandheads of stars over nearly the full range of velocities encountered. Velocities were derived by interpolating the measurements to four times finer spectral spacing followed by calculating cross correlations

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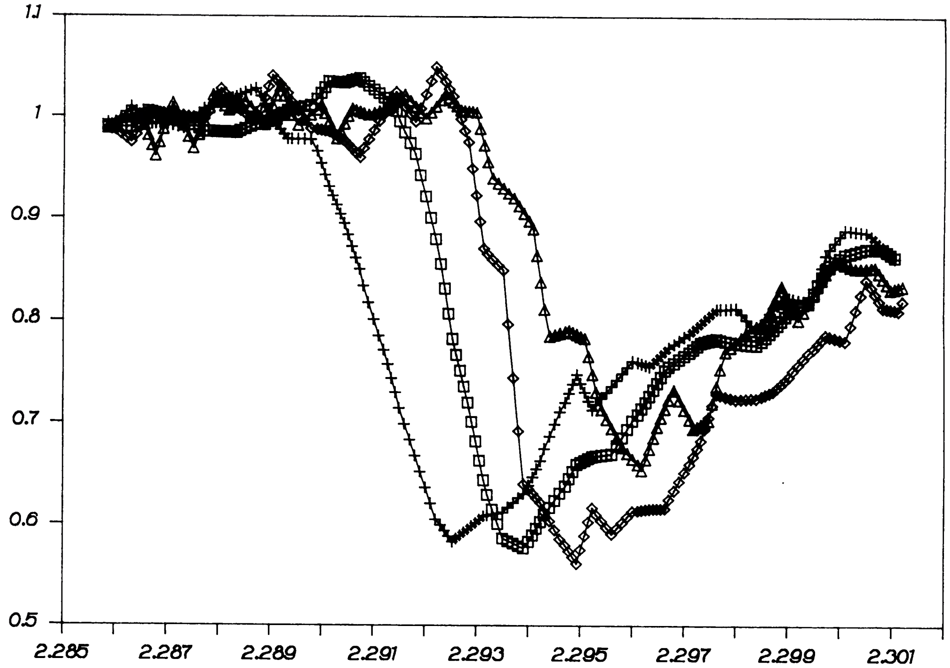

FIG. 1.—CO bandhead spectra of Galactic center stars. In the nomenclature of Table 1, the stars are numbers 40, 1 (IRS 7), 50, and 16 (BHA 33), giving a velocity range of -314 to $+110$ km s^{-1}.

of the individual source spectra with those of IRS 7 obtained before and after the measurement and interpolating between the two estimates according to the trend of IRS 7 velocities for the night. The observation of the largest radial velocity was followed by a failure of the telescope chopping secondary mirror which made it impossible to follow up with a measurement of IRS 7; we consider this measurement to be provisional.

Table 1 summarizes the velocity measurements from this work along with those for OH/IR stars from Winnberg *et al.* (1985), those for IRS 19 and IRS 23 from Sellgren *et al.* (1987), and the adopted value for IRS 7. Sources are indicated by the most commonly used names except for unnamed stars located in large-scale imaging mosaics of this region (Rieke 1986 and unpublished work). The locations of the outlying stars are indicated in Figure 2. Figure 1 in Paper I will assist in identifying sources within the central 2 pc. All physical scales in this *Letter* are calculated under the assumption that the Galactic center is at a distance of 8 kpc.

III. DISCUSSION

In assessing the mass distribution around the Galactic center, it is desirable to use constraints placed by measurements of emission-line velocities for the gas in this region as reviewed by Lugten *et al.* (1986), Gusten (1987), Genzel and Townes (1987), and Serabyn *et al.* (1988). The motion of the inside edge of the molecular ring is dominated by rotation at a tangential velocity of 110 to 130 km s^{-1} at a radius of 1.4 to 2 pc from Sgr A*. As one goes outside this radius, it becomes progressively less obvious that the gas detected is part of this ring (Lugten *et al.* 1986; Gusten 1987). Inside the ring, the gas motions show increasing velocities which indicate the presence of a dominant central mass if the gas is controlled by gravitational forces (Serabyn *et al.* 1988). We will use the rotation of the inner portion of the molecular ring as a constraint on models of the mass distribution, but otherwise will use only the stellar velocities to compare results with the gas inside and outside 2 pc radius.

The most straightforward way to look at the mass implied by the stellar velocities is to compute the velocity dispersion as a function of radius, as in Table 2. Although a systematic rotation might be expected, Winnberg *et al.* (1985) estimate it to be an order of magnitude below the typical velocities, and it is not apparent in our data. Thus, no corrections have been applied to the observed velocities in computing their dispersion. The values are virtually independent of distance from Sgr A*. This behavior contrasts with the gas motions for 2 pc $< r <$ 10 pc described by Lugten *et al.* (1986) and may indicate that their data are influenced by blending with velocity components along the line of sight, as they discuss (see also Gusten 1987).

The simplest model with a central black hole that dominates the mass within 2 pc would have velocity disperson increasing as $r^{-1/2}$; clearly, there is no indication of this trend in our data. A χ^2 analysis indicates that there is a 95% probability that the stellar velocity dispersion for $r < 0.5$ pc (average radius $\langle r \rangle = 0.36$ pc) is less than 120 km s^{-1}. Perhaps the most important result of this *Letter* is that the upper limit of 120 km s^{-1} for the stellar velocity dispersion within 0.5 pc of Sgr A* is far below the velocities observed for the gas in this region, which range over ± 300 km s^{-1} (Serabyn *et al.* 1988). Because our estimate of the rms stellar velocity error is small compared with the measured velocities, this discrepancy is unaffected if we have overestimated our errors; if we have underestimated them, the discrepancy becomes even larger.

A similar χ^2 analysis shows a 95% probability that the stellar velocity dispersion for 1 pc $< r <$ 2 pc ($\langle r \rangle = 1.4$ pc) is greater than 55 km s^{-1}. The average projected radii for these two sets of stars differ by a factor of 4; the statistical likelihood that the stellar velocity dispersion goes as $(r_1/r_2)^{-1/2} = 2$ over this range is therefore under 1%. This result can be contrasted with the rotation curve deduced from gas velocities, which increases dramatically inward toward Sgr A* and is

TABLE 1

VELOCITY MEASUREMENTS

Number	Name	r (pc)	Velocity (km s^{-1})
1.........	IRS 7	0.22	−128
2.........	IRS 1	0.28	+35
3.........	IRS 12N	0.31	−24
4.........	IRS 14	0.34	+4
5.........	OH 359.951 − 0.05	0.35	−27
6.........	BHA 4	0.35	+78
7.........	IRS 12S	0.39	+73
8.........	IRS 10E	0.41	−156
9.........	IRS 15	0.45	−32
10.........	BHA 17	0.48	+1
11.........	BHA 27	0.53	−75
12.........	BHA 2	0.58	−110
13.........	IRS 17	0.62	+77
14.........	IRS 11	0.65	−10
15.........	IRS 18	0.81	+25
16.........	BHA 33	0.81	+110
17.........	...	0.87	−76
18.........	BHA 26	0.87	−130
19.........	...	0.93	−1
20.........	...	0.93	−18
21.........	BHA 35	0.95	−44
22.........	IRS 19	1.02	+34
23.........	OH 359.94 − 0.05	1.04	+53
24.........	IRS 22	1.05	−160
25.........	...	1.06	−35
26.........	...	1.12	−121
27.........	...	1.22	−20
28.........	OH 359.953 − 0.041	1.50	+70
29.........	...	1.60	+105
30.........	...	1.79	−49
31.........	OH 359.951 − 0.035	1.81	+82
32.........	...	1.91	−14
33.........	IRS 23	1.96	−39
34.........	...	2.06	+67
35.........	...	2.15	−43
36.........	...	2.59	−67
37.........	OH 359.93 − 0.06	2.85	−95
38.........	...	3.56	+109
39.........	...	3.66	+178
40.........	...	3.71	−314
41.........	...	4.13	+17
42.........	...	4.15	−46
43.........	...	4.32	−28
44.........	OH 359.94 − 0.08	4.34	−82
45.........	...	4.68	−8
46.........	...	4.99	+47
47.........	OH 359.91 − 0.04	5.21	−141
48.........	...	5.36	+33
49.........	...	5.48	−51
50.........	...	5.50	+12
51.........	...	5.62	−55
52.........	...	5.64	−66
53.........	...	6.14	−41
54.........	OH 359.99 − 0.06	6.15	+13

NOTE.—BHA sources: Bailey, Hough, and Axon 1984.

consistent with an $r^{-1/2}$ dependence over the same range of radius (Genzel and Townes 1987; Serabyn *et al.* 1988).

Systematic errors, such as those connected with the stellar orbital eccentricities, can dominate the statistical ones discussed above (e.g., Sargent 1987). However, our situation is the opposite of that usually encountered, in which a limited increase in central velocity dispersion can be explained by including stars with highly eccentric orbits rather than invoking a black hole (e.g., Richstone and Tremaine 1985 and references therein). If the mass distribution in the Galactic center is dominated by a black hole, a systematic decrease in orbital eccentricity hides the effect of the hole on the stellar motions.

TABLE 2

VELOCITY DISPERSION

Radius (pc)	v_d[a] (km s^{-1})
$r < 0.5$	72
$0.5 < r < 1.0$	72
$1 < r < 2$	75
$2 < r < 6.5$	99[b]

[a] Measured dispersions corrected for a uniform assumed error of 20 km s^{-1} (rms).

[b] 74 km s^{-1} with highest velocity star excluded.

Bahcall and Tremaine (1981) discuss the projected mass method to analyze velocity dispersions and show how systematic errors can affect the masses derived from stellar velocities. The enclosed mass is given by

$$M = [C/(\pi GN)]\left[\sum v_{zi}^2 r_i\right], \qquad (1)$$

where G is the gravitational constant, N is the number of stars, v_{zi} is the radial velocity of the ith star, and r_i is the projected distance of this star from the center of the system. For the case where the gravitational field is dominated by a central point mass, $C = 32/3$ for circular stellar orbits, 16 for an isotropic velocity distribution, and 32 for linear or plunging orbits. Heisler, Tremaine, and Bahcall (1985) extend this analysis to a self-gravitating system. The primary correction in this case is to double the values of C. In both cases, the fractional statistical error can be estimated as $1.4N^{-1/2}$.

Table 3 summarizes the mass estimates using the projected mass approach. The dominant point source and purely self-gravitating system represent the extremes the actual mass distribution may take. They can be compared with the mass determined from the rotation of the molecular ring at a radius of 2 pc; the range of possible masses from this latter determination corresponds to rotational velocities of 110 to 130 km s^{-1}. This range is a lower limit on the uncertainties in the mass within the molecular ring because there are significant noncircular motions within it (e.g., Gusten 1987). Even if we ignore these additional uncertainties, it can be seen that either mass

TABLE 3

ENCLOSED MASS[a] AS A FUNCTION OF RADIUS AROUND SAGITTARIUS A*

Radius (pc)	N	Linear Orbits	Isotropic Velocities	Circular Orbits	Molecular Ring
		Dominant Central Mass			
<0.5.........	10	4.2 ± 1.8	2.1 ± 0.9	1.4 ± 0.6	...
<1.0.........	21	6.8 ± 2.0	3.4 ± 1.0	2.3 ± 0.7	...
<2.0.........	33	10.6 ± 2.6	5.3 ± 1.3	3.5 ± 0.9	5.6–7.9
<6.5.........	54	40 ± 8	20 ± 4	13 ± 3	
		Self-Gravitating System			
<0.5.........	10	8.4 ± 3.8	4.2 ± 1.9	2.8 ± 1.2	...
<1.0.........	21	14 ± 4	6.8 ± 2.1	4.5 ± 1.4	...
<2.0.........	33	21 ± 5	10.6 ± 2.6	7.1 ± 1.7	5.6–7.9
<6.5.........	54	81 ± 16	40 ± 8	27 ± 5	...

[a] Units of mass are $10^6\ M_\odot$.

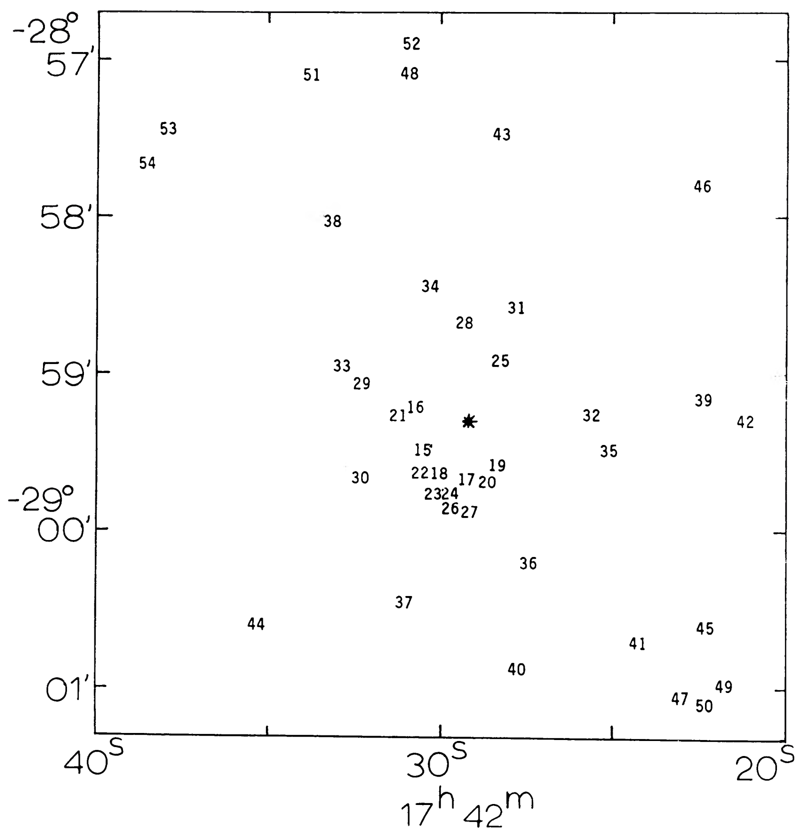

FIG. 2.—Location of stars measured in the Galactic center. Stars are coded by number from Table 1. Within the central 2 pc, locations can be determined from Fig. 1 of Paper I.

distribution within the molecular ring is consistent with the rotation at 2 pc. If there is a dominant point source, relatively low ring rotational velocities and an isotropic stellar velocity distribution or even more eccentric stellar orbits are favored. If the stellar system is purely self-gravitating, relatively high ring velocities and less eccentric orbits are favored.

However, the stellar velocities indicate that the enclosed mass falls steadily within the 2 pc radius, so the results are formally inconsistent with the dominant central mass model. The enclosed mass within 0.5 pc is 0.4 ± 0.2 times that enclosed within 2 pc; this result is independent of many of the modeling parameters, except for the possibility that there is a very strong systematic change in the stellar orbital eccentricities over this distance. Unless this somewhat contrived situation holds, the projected mass method indicates that the mass is distributed over the central 2 pc radius and presumably resides in the stars or is shared between stars and a central mass.

In reaching this conclusion, we have assumed that we could ignore the effects of stars projected from the foreground or background onto a position near Sgr A*. In Paper III, we show that the brightest stars around the Galactic center are very strongly concentrated within the 2 pc radius region centered on Sgr A*. By necessity, these are the stars for which we have measured radial velocities, so we can assume that the stars that appear to lie in this region are actually within it, not projected onto it. From a typical brightness for stars we measured spectroscopically and the stellar distributions discussed in Paper III, it can be shown that roughly 0.4 such interlopers are expected in the radial velocities for $r < 0.5$ pc and six for $r < 2$ pc. Let us assume instead that we have two interlopers within 0.5 pc; there is a formal probability of ~ 0.01 that there would be more than two such stars. In addition, assume they are the two stars with lowest radial velocities, and that the six additional interlopers expected out to $r = 2$ pc have velocities typical of the stars in that region. In good agreement with the previous estimate, we find that the mass within 0.5 pc is 0.5 times that within 2 pc, the difference being at a 2 σ level of significance. Thus, our ignoring interlopers seems justified. The basic reason is that a much higher proportion of very high velocity stars is needed in the central parsec if its mass is to be increased, and removing stars cannot satisfy this need efficiently.

Just as with the stars, uncertainties in orbital parameters lead to large uncertainties in modeling the mass distribution from the gas motions inside the molecular ring. Moreover, the previous concerns that the gas is subject to significant nongravitational forces are supported by the differences in velocities reported here between the stars and gas. There are a variety of plausible candidates for these forces. First, Aitken *et al.* (1986) find a *lower limit* to the magnetic field strength that requires that its energy density be within a factor of ~ 4 of the kinetic energy density in the cloud motions (see also Genzel and Townes 1987). The extremely elongated feature along the "northern arm" (Morris and Yusef-Zadeh 1987; Lo 1987) is suggestive of some mechanism such as magnetic confinement. Second, Gatley *et al.* (1984, 1986) hypothesize an isotropic wind of $3 \times 10^{-3}\ M_\odot\ \mathrm{yr}^{-1}$ at 750 km s^{-1} emanating from the central region to excite the molecular hydrogen in the molecular ring. If it is assumed that any gas cloud exposed to the wind absorbs the associated momentum, one can show that the force from the wind will dominate gravity over a significant skin depth for the densest clouds observed and may be dominant over the entire gas cloud at lower densities. In the absence of some confinement mechanism, such as a strong magnetic field, such a wind might be expected to disrupt the clouds relatively quickly. Other mechanisms for cloud disruption are discussed in Lacy *et al.* (1980); for example, the gas clouds may collide with each other on a reasonably short time scale.

It is unclear whether the stellar velocity dispersion requires an increase in M/L in the central parsec. If the stellar distribution has a core radius of the order of 0.1 pc, as has been suggested in the past and used in modeling the gas motions, then the stellar velocities are compatible with constant M/L over the entire range of our measurements. If, however, the core radius is significantly larger, $r_c \approx 0.6$ pc (Paper III), then an additional nonluminous mass of $\sim 2 \times 10^6\ M_\odot$ is indicated. This mass need only lie within the central 2 pc diameter; there is no requirement that it be concentrated into a central black hole.

It has recently been found that both M31 and M32 have $3\text{–}10 \times 10^6\ M_\odot$ of dark matter in their nuclei (Tonry 1987; Kormendy 1988; Dressler and Richstone 1988). Despite the much higher level of activity apparent in the Galactic center, it has no more and probably less unseen nuclear mass.

IV. CONCLUSION

Radial velocities of 54 stars within 6.5 pc of the Galactic center place constraints on the mass distribution within this region.

1. Between 0.36 and 6.5 pc, the velocity dispersion is roughly independent of distance from Sgr A*, indicating the predominance of an extended mass distribution.

2. The stellar velocities inside 2 pc are significantly less than those of the gas, suggesting that the gas is subject to nongravitational forces.

3. If the core radius of the stellar distribution is ~ 0.1 pc, as has been found by a number of workers, there is no requirement for unseen mass in the Galactic center; if the core radius is larger, an unseen mass of up to $\sim 2 \times 10^6\ M_\odot$ is possible.

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