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THE MASS DISTRIBUTION IN THE VICINITY OF THE GALACTIC CENTER

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ABSTRACT

The case for a massive black hole in the center of the Galaxy is reassessed using improved modeling techniques and observational data. A dark mass of $\sim 2 \times 10^6 M_\odot$ is present within 0.2 pc of the Galactic center. However, the available data can be modeled, without appealing to a massive black hole, using an extended distribution of dark stellar remnants (neutron stars and stellar mass black holes) provided that the stellar initial mass function in the central parsec is deficient in stars less massive than $\sim 1 M_\odot$. Such a situation may be a natural consequence of repeated gas build-up followed by starbursts in the central region. A clear distinction between this and the massive central black hole model cannot be made using red giant tracers outside 0.2 pc due to uncertainties in the radial velocity dispersion distribution. The cluster of massive early-type emission-line stars in the central parcsec more effectively probe the mass distribution close to Sgr A*, but their small number and partial rotational support complicate mass determinations. Proper motion determinations for stars within 0.5″ of Sgr A* may be the most effective means of unambiguously determining the mass distribution in the immediate vicinity of the Galactic center.

Key Words : Galaxy: center

I. INTRODUCTION

The center of our galaxy contains the closest galactic nucleus. Here we can study processes which may help unravel the complex phenomena occurring in more distant active galactic nuclei. Central to this goal is a determination of the role played by a possible massive ($\sim 10^6 M_\odot$) black hole in our Galactic center. The presence of a massive black hole in the Galactic center is suggested by the existence of the unique radio source Sgr A* apparently at the dynamical center of the Galaxy (Backer & Sramek 1987). The radio emission from Sgr A* is explicable in terms of low-level accretion onto a central black hole of mass $\sim 10^6 M_\odot$ (Melia 1994; Narayan, Yi, & Mahadevan 1995). However, current low limits on the near- and mid-infrared flux from Sgr A* (Eckart et al. 1995) place tight constraints on these models. It is unclear whether accretion onto a significantly lower mass black hole can provide an alternative explanation for this unique object. Any central black hole is currently energetically insignificant, with the central stellar cluster being responsible for most of the ionizing flux, luminosity, and wind from the central region (Allen, Hyland, & Hillier 1990; Krabbe et al. 1991; Krabbe et al. 1995). Dynamical estimates of the central mass profile remain the strongest indicators of the existence of a massive, compact, central mass concentration. This mass profile has been probed using studies of both gas (e.g., Serabyn et al. 1988; Roberts, Yusef-Zadeh, & Goss 1996) and stellar kinematics (McGinn et al. 1989; Sellgren et al. 1990; Krabbe et al. 1995; Haller et al. 1996). The latter studies have demonstrated the remarkable fact that the projected stellar velocity dispersion increases from ~ 50 km s^{-1} at 4 pc ($\sim 100''$) to ~ 120 km s^{-1} at 0.2 pc ($\sim 5''$) from Sgr A*. It is this feature of the stellar distribution which points most strongly to the presence of a massive compact object in the Galactic center.

In this contribution, we summarize our recent efforts to establish how rigorously a central massive black hole is required by the available stellar kinematic data. We begin by reviewing the model of Saha et al. (1996) which accounts for pre-1995 data without the need for a central massive black hole. We then apply this model to the more recent data of Genzel et al. (1996). We conclude with a comparison of the modeling techniques of Saha et al. (1996) and Genzel et al. (1996), and suggest ways in which progress can be made.

II. A MODEL WITH NO BLACK HOLE

We were motivated to reanalyze the stellar dynamics in the Galactic center for several reasons: First, Allen (1994) showed that the cool stellar population displaying 2.3 μm CO absorption has a different spatial distribution to the total light distribution used previously. Second, the analyses by McGinn et al. (1989) and Sellgren et al. (1990) neglected the effect of projection on the stellar velocity dispersion. This has a moderate effect on the inferred mass distribution. Third, accurate mass and deprojected light distributions are necessary when comparing enclosed mass and enclosed light in order to derive the appropriate mass-to-light ratio. This is important when making inferences about the existence of a massive black hole.

Saha et al. (1996) modeled the mass distribution in the Galactic center using the Allen (1994) cool star surface brightness distribution and velocity dispersion data appropriate to the cool star population from McGinn et al. (1989), Sellgren et al. (1990), and

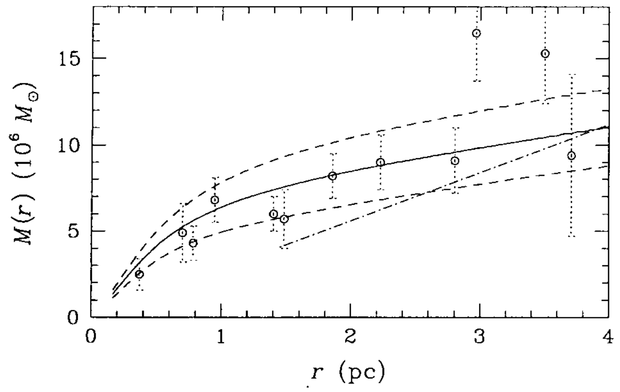

Fig. 1.— Enclosed mass (*solid line*) as a function of radius from Saha et al. (1996). The dashed curves are 1σ error estimates from Monte Carlo variation of the kinematic data. The points with dashed error bars are enclosed mass estimates from McGinn et al. (1989). The enclosed mass estimates from Güsten et al. (1987) are indicated by a dot-dashed line.

Lindqvist et al. (1992). Our modeling technique involved deprojection of fits to the observational data, followed by application of the spherical Jeans equation. The derived enclosed mass profile is shown in Fig. 1 as a function of true radial distance, and in Fig. 2 as a function of total enclosed K luminosity at the same radius. Under the assumptions that the system is spherical and isotropic, we confirmed the existence of $\sim 3 \times 10^6\ M_\odot$ within 0.35 pc of the Galactic center, and $\sim 1.5 \times 10^6\ M_\odot$ within 0.2 pc (Fig. 1). However, we found that M/L_K varied from ≤ 1 outside a radius of 0.8 pc to > 2 at 0.35 pc (Fig. 2). This behavior cannot be due to the presence of a central massive black hole; M vs L_K for a dominant central black hole would show a straight line with non-zero intercept on the mass axis. We suggested that this varying M/L_K could be due to an increasing concentration of stellar remnants toward the Galactic center. This extended dark mass distribution would be in the form of stellar mass black holes, neutron stars, and possibly white dwarfs. This explanation was partially motivated by the correspondence between the radius at which M/L_K increased and the radial extent of the compact cluster of young massive He I emission-line stars within 1 pc of the Galactic center. The existence of these stars demonstrates that the central region underwent a significant starburst $\sim 10^7$ yr ago when gas densities in this region must have been much higher than the present low value. A simple model for the star formation history in the central parsec of the Galaxy suggested that this M/L_K could arise from repeated periods of gas accumulation followed by rapid starbursts if the initial mass function of stars formed during the burst is deficient in stars less massive than $\sim 1\ M_\odot$.

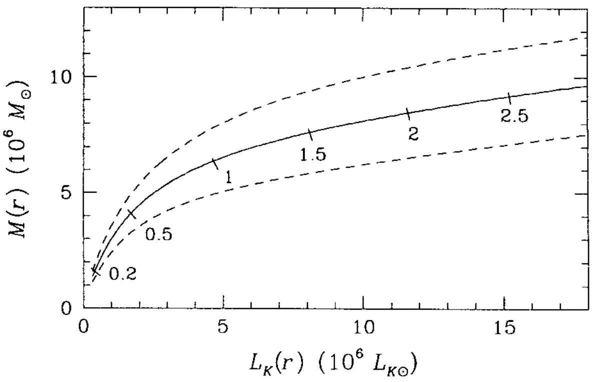

Fig. 2.— Enclosed mass at given radius versus total enclosed K band luminosity in the same volume from Saha et al. (1996). Tick marks along the curve indicate the corresponding radii in parsecs.

III. INFERENCES FROM NEW DATA

The above analysis was based on projected stellar velocity dispersions derived from 2.3 μm CO absorption bandhead spectra of diffuse light between bright stars (McGinn et al. 1989; Sellgren et al. 1990). These data are shown along with our fit in Fig. 3. The cool star projected velocity dispersion profile has recently been remeasured using diffuse light at one slit position (Haller et al. 1996), and discrete velocities of $\sim$ 200 late-type stars within the central 2 pc (Genzel et al. 1996). These data are shown in Fig. 4 along with the Genzel et al. (1996) fit. Genzel et al. (1996) used these data, and their surface density profile, to derive a mass profile for the Galactic center which is dominated by a central $3 \times 10^6\ M_\odot$ black hole. It is clearly of interest to establish how these analyses differ.

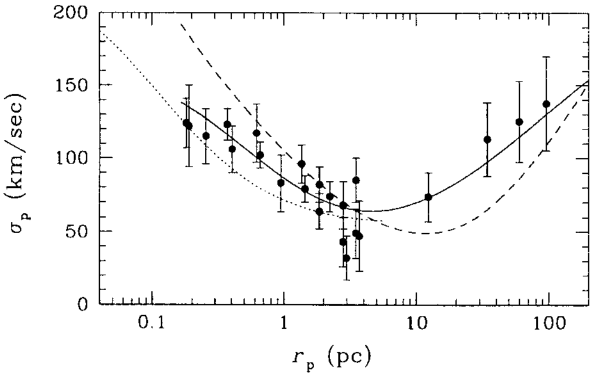

Fig. 3.— Projected stellar velocity dispersion for cool stars vs projected radius from Saha et al. (1996). The solid curve is our fit to the projected data. The dashed curve is its deprojection. Data within 4 pc are from McGinn et al. (1989) and Sellgren et al. (1990). Data between 10 and 100 pc are from Lindqvist et al. (1992). The dotted curve is the Genzel et al. (1996) fit from Fig. 4.

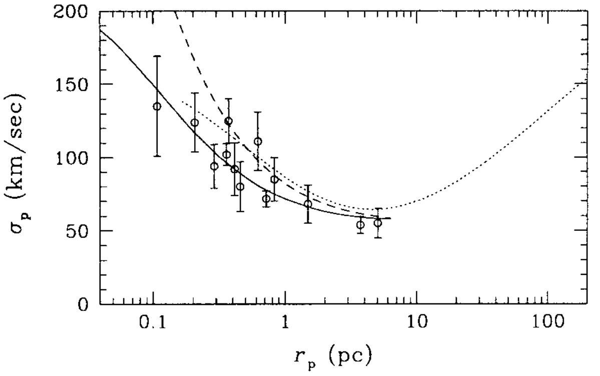

Fig. 4.— Projected stellar velocity dispersion for cool stars vs projected radius from Genzel et al. (1996). The solid curve shows their fits to the projected data. The dashed curve is its deprojection. The dotted curve is the Saha et al. (1996) fit from Fig. 3.

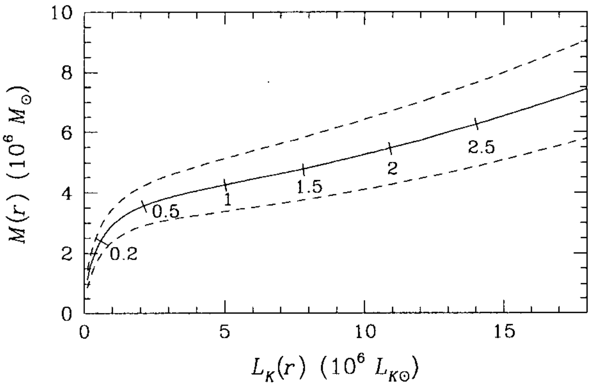

Fig. 5.— Result of running the Saha et al. (1996) model on the Genzel et al. (1996) input data (plotted as in Fig. 2).

Figs. 3 and 4 reveal significant systematic differences in the basic velocity dispersion data on which the two analyses are based, particularly in the 0.5–2 pc radius range. The lower velocity dispersions measured by Genzel et al. (1996) lead to lower enclosed masses in this radius range. Further investigation of these discrepancies is warranted.

We have rerun our model using the Genzel et al. (1996) velocity dispersion data and obtain a qualitatively similar result to that reported in Saha et al. (1996). Specifically, we derive an enclosed mass within 0.2 pc of 2.4 × 10^6 $M_\odot$, and find that the local M/L_K now increases within 0.5 pc of Sgr A* (Fig. 5). This weakens our previous association of the turn-over point with the extent of the He I star cluster. Our fit to the Genzel et al. (1996) velocity dispersion data is shown in Fig. 6, superposed on their fit. Both curves fit the data equally well, but ***it appears to be the functional forms of the velocity dispersion fits which lead to the different black hole inferences.*** Our fit to the projected velocity dispersion is a quartic polynomial in the variable $u = \ln(r_{p,0} + r_p)$, so remains finite at $r_p = 0$. Genzel et al. (1996) fit the radial velocity dispersion with a power-law in radius which becomes infinite at $r = 0$. The presence or absence of a massive black hole may therefore be built into the Genzel et al. (1996) and Saha et al. (1996) analyses, respectively, through the choice of fitting function for the velocity dispersion distribution. Subtle differences in the curvature of the projected velocity dispersion distribution in the inner regions cannot easily be discerned, so the true form of the velocity dispersion distribution cannot be determined.

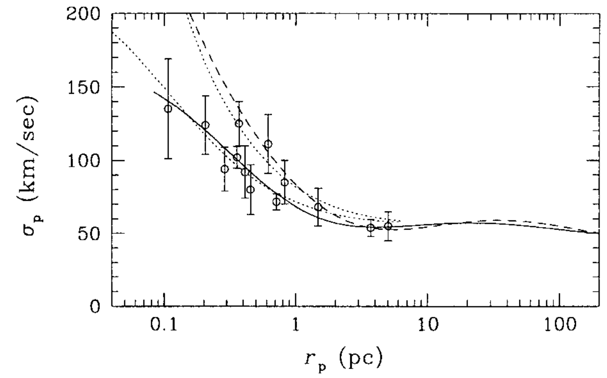

Fig. 6.— Projected stellar velocity dispersion for cool stars vs projected radius showing our fit to the Genzel et al. (1996) data. Dotted lines are the Genzel et al. (1996) fits from Fig. 4.

The He I emission-line stars in the central 1 pc have a smaller core radius, and so probe the mass distribution closer to Sgr A*. The 25 He I emission-line stars measured by Genzel et al. (1996) appear to rotate about an E-W axis with a velocity of $\sim$ 120 km s^{-1}. The precise nature of this rotation, and the small number of objects, complicate mass profile determinations based on these stars; the inferred velocity dispersion depends strongly on the rotational model adopted. These stars also have strong stellar winds which may influence the derived velocity dispersions.

For these reasons, it is unlikely that a Jeans equation analysis will lead to an unambiguous determination of the Galactic center mass profile. We are currently investigating alternative analysis procedures based on finite samples of discrete stellar velocities.

IV. FUTURE PROSPECTS

Radial velocity measurements of stars much closer to Sgr A* will be required to unambiguously test the central massive black hole model. Within 0.02 pc ($0.5''$) of Sgr A*, the radial velocity dispersion due to a 10^6 $M_\odot$ black hole may be $\geq$ 500 km s^{-1}. The high angular resolution K band image of Eckart et al. (1995) shows a compact cluster of $\sim$ 10 stars within this region. Proper motions for these stars promise to provide the required velocity information to definitively test the massive black hole model. Several experiments are currently planned, or underway, to make these difficult measurements.

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