THE STELLAR CLUSTER

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ABSTRACT. Observations of the stellar cluster in the central 10 pc of the Galaxy are reviewed. The stellar density law derived from the observed light distribution and the effects on this density law of variable extinction, the possibility of a varying mass-to-light ratio, and the current debate as to the core radius of the cluster are all important for establishing the true mass distribution of the stellar cluster. The presence of the supergiant IRS 7 in the Galactic Center establishes that some recent star formation has occurred, but the age and extent of a possible starburst are still being established. The kinematics of the stellar cluster show predominantly velocity dispersion, in contrast to the systematic gas motion observed, yet the total mass distributions derived from stellar and gas kinematics agree reasonably well. The core radius of the cluster is critical to establishing whether or not a central dark mass is required to explain the total mass distribution.

1. Characteristics of the Stellar Cluster

The center of our Galaxy is the home of a very dense stellar cluster, which is strongly concentrated in the vicinity of the infrared source IRS 16 and the compact nonthermal radio source Sgr A* (Becklin and Neugebauer 1968, 1975). Visual extinction of 30 mag toward the Galactic Center (Becklin and Neugebauer 1968) prevents these stars from being observed at visual wavelengths. Thus, infrared observations and radio observations provide the only windows for study of this cluster. Observations at 2.2 μm, which are dominated by the light of late-type giants and supergiants, are affected only by about 3 mag of extinction (Becklin and Neugebauer 1968). Radio observations of OH/IR stars in the stellar cluster are unaffected by intervening dust.

The surface brightness of starlight at 2.2 μm is observed to depend on galactocentric radius r as $r^{0.8\pm0.1}$, over radii of $\sim 1''$–$600''$ (Becklin and Neugebauer 1968; Sanders and Lowinger 1972; Bailey 1980; Allen, Hyland, and Jones 1983), or $\sim$0.05–25 pc, assuming a distance to the Galactic Center of 8.5 kpc. This radial dependence of surface brightness implies that the density of stars, $n_\star(r)$, is proportional to $r^{-1.8\pm0.1}$. This is close to the density law expected for an isothermal stellar cluster, $n_\star(r) \sim r^{-2}$. This derivation of stellar density from 2.2 μm surface brightness, however, depends on two assumptions: that the intervening extinction is constant across the stellar cluster and that the average luminosity per star, or equivalently the mass-to-light ratio, M/L, is constant with radius. Infrared observations by Becklin and Neugebauer (1978), Lebofsky (1979), Allen, Hyland, and Jones (1983), Glass, Catchpole, and Whitelock (1987), and Gatley, DePoy, and Fowler

M. Morris (ed.), The Center of the Galaxy, 477–486.

(1988) show variable, patchy extinction across the stellar cluster that could affect the observed stellar brightness distribution. The possibility of a radial change in M/L is an important issue to consider, particularly in light of the differences inferred between the stellar mass distribution derived from the 2.2 μm surface brightness and the total mass distribution derived from the kinematics of stars and gas (Genzel and Townes 1987).

Another key issue for understanding the spatial distribution of the stellar cluster is determining the core radius of the cluster. Bailey (1980) analyzed 2.2 μm observations by Becklin and Neugebauer (1968, 1975) and found the core radius was $\leq$0.1 pc. Allen, Hyland, and Jones (1983), with higher resolution 2.2 μm data, placed an upper limit on the core radius of 0.08 pc. Both of these studies considered the total 2.2 μm light of the stellar cluster and assumed that IRS 16 was the center of the cluster. More recently, Rieke and Lebofsky (1987) have argued that the core radius is best measured by the fainter stars, which dominate the mass of the stellar cluster. These faint stars are observed as diffuse light inbetween the individual bright stars observed on infrared images. From this faint starlight they derive a core radius of 0.6–0.8 pc, much larger than the core radius derived from the total starlight. Rieke and Lebofsky (1987) assumed Sgr A* is the center of the stellar cluster, rather than IRS 16. The choice of a center for the stellar cluster has a large effect on the derived core radius, as there is little or no 2.2 μm radiation within 0.04 pc of Sgr A* (Allen and Sanders 1986; Rieke, Rieke, and Paul 1988), while IRS 16 is composed of at least three bright infrared sources that may be in themselves dense clusters of stars (Storey and Allen 1983). Another problem is that the core radii of the brighter and fainter stars may be different, as suggested by the observations; this would imply a change in the stellar population with galactocentric radius, which complicates the derivation of the stellar mass distribution from the observed stellar surface brightness distribution. The true value of the core radius, and the true mass distribution of the stellar cluster, are crucial to understanding whether or not a central dark mass, in addition to the mass of the stellar cluster, is required to explain the total mass distribution derived kinematically; this point is discussed further in section 4.

2. Has There Been Recent Star Formation in the Galactic Center?

Observations of CO absorption at 2.3 μm in bright individual stars in the Galactic Center have identified most of these stars as late-type giants or supergiants (Neugebauer *et al.* 1976; Treffers *et al.* 1976; Wollman, Smith, and Larson 1982; Lebofsky, Rieke, and Tokunaga 1982; Sellgren *et al.* 1987; Rieke and Rieke 1988a; Rieke, Rieke, and Paul 1988). Lebofsky, Rieke, and Tokunaga (1982) classified six bright 2.2 μm sources as M supergiants, based on their 2 μm spectra, and argued on the basis of this high density of supergiants that there must have been a burst of massive star formation 10 Myr ago. Sellgren *et al.* (1987), in contrast, argued that the presence of H_2O vapor absorption as well as CO absorption in all but one of these stars led to reclassifications as giants rather than supergiants. The strength of the H_2O absorption, however, could be affected by higher metallicity in the Galactic Center. The luminosity class of the brightest stars in the Galactic Center is interesting because supergiants form from very massive and short-lived stars, implying very recent star formation, while giants can evolve from lower-mass stars, implying an older population. The absolute magnitudes of most of the brightest stars are intermediate between giants and supergiants, leaving the luminosity question unresolved at present.

The brightest infrared source in the central stellar cluster, IRS 7, is definitely an early M supergiant, based on the strength of its CO absorption and also on its absolute magnitude (Lebofsky, Rieke, and Tokunaga 1982; Sellgren *et al.* 1987). IRS 7 is probably in the Galactic Center, rather than being a foreground or background star, based on several arguments. Yusef-Zadeh, Ekers, and Morris (1988) have detected radio continuum emission from IRS 7, while Rieke and Rieke (1988b) have detected Brackett-α emission from IRS 7. These authors have argued that the stellar wind of IRS 7 is ionized by the UV source that ionizes the central 2 pc of the Galaxy, thus placing IRS 7 within 2 pc from the Galactic Center. Geballe, Baas, and Wade (1988) have detected absorption features in IRS 7 from cold gas at velocities typical of either the circumnuclear ring or a cloud behind Sgr A West; this places IRS 7 either within 2 pc of the Galactic Center or a few pc behind it. The high radial velocity of IRS 7 (-130 km s^{-1}; Sellgren *et al.* 1987) is characteristic of stellar velocities observed within 1 to 100 pc of the Galactic Center (Winnberg *et al.* 1985; Sellgren *et al.* 1987; Rieke and Rieke 1988a; Lindqvist *et al.* 1988). Thus the presence of at least one supergiant in the center of the Galaxy, with an age of about 40 Myr (Lebofsky and Rieke 1987), is established. The question becomes, then, not whether star formation has occurred, but how much star formation and how recently.

Another approach to determining whether a recent burst of star formation has occurred is to study the luminosity function of stars in the Galactic Center. Lebofsky and Rieke (1987) have compared the absolute magnitudes of stars in the central 12 pc of the Galaxy with the absolute magnitudes of stars in Baade's window. They find that the Galactic Center has an excess of very luminous stars compared to Baade's window. From this they conclude that a burst of star formation must have occurred in the Galactic Center 100 Myr ago.

3. Stellar Kinematics

Stellar kinematics have been observed both at radio wavelengths, by using the OH maser velocities of OH/IR stars, and at infrared wavelengths, by using the velocity determined from the 2.3 μm CO absorption band in late-type stars. Studies of OH/IR stars have concentrated on large scale kinematics, over a 5–150 pc distance from the Galactic Center (Habing *et al.* 1983; Winnberg *et al.* 1985; Lindqvist *et al.* 1988). The infrared studies have used either individual bright stars (Sellgren *et al.* 1987; Rieke and Rieke 1988a) or the integrated starlight of the fainter stars (McGinn *et al.* 1989), and have concentrated on a radius of 6 pc from the Galactic Center.

Sellgren *et al.* (1987) measured the radial velocities of six individual late-type stars within a 2 pc radius of the Galactic Center. They combined these observations with velocities of seven OH/IR stars within a 6 pc radius (Winnberg *et al.* 1985) to study a total of 13 stars. Rieke and Rieke (1988a) have recently published radial velocity measurements of 54 stars within a 6 pc radius of the Galactic Center, greatly increasing the number of stars and thus reducing the uncertainty in the derived kinematic quantities. In a different approach, McGinn *et al.* (1989) have observed the 2.3 μm CO bandhead of the integrated starlight in the Galactic Center. They directly measured the average rotational velocity and velocity dispersion at each position observed with their 0.8 pc diameter beam. They observed positions along the Galactic plane at $r = 0.4$–4 pc, and along the minor axis of the Galaxy at $r = 0.7$–1.5 pc.

The observations of stellar velocities show that velocity dispersion strongly dominates the stellar kinematics and that only small amounts of rotation are present (Winnberg *et al.* 1985; Sellgren *et al.* 1987; Rieke and Rieke 1988a; McGinn *et al.* 1989; Lindqvist *et al.* 1988). In contrast, the kinematics of gas in the Galactic Center, reviewed by Genzel and Townes (1987) and more recently within this volume (Genzel 1988; Serabyn 1988; Lacy 1988), are dominated by systematic motion, with the observed rotational velocities generally larger than the observed velocity dispersions. There is no correspondence between stellar and gas velocities along the same line of sight (Sellgren *et al.* 1987). The stellar and gas kinematics are completely different, as can be seen from the importance of systematic motion for the gas velocities and the dominance of velocity dispersion for the stellar motions.

Definite rotation is observed in the velocities of integrated starlight for $r < 3$ pc in the Galactic Center (McGinn *et al.* 1989). The velocities of the individual stars measured by Rieke and Rieke (1988a), averaged in bins of galactocentric radius projected along the Galactic plane, agree very well with the average velocities of integrated starlight (McGinn *et al.* 1989) measured along the plane. This comparison is shown in Figure 1. The stellar

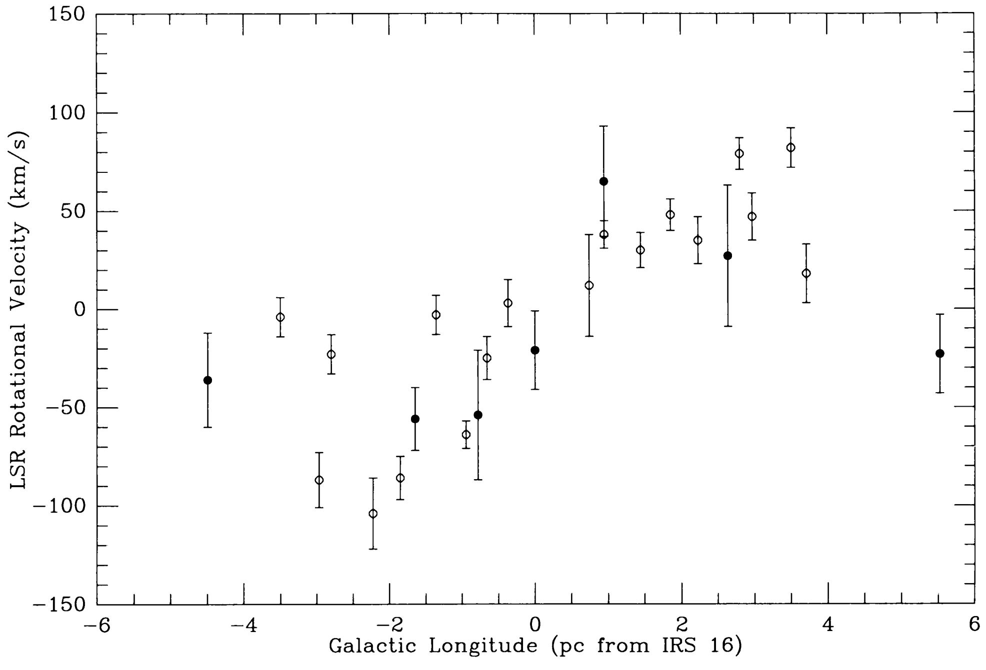

Fig. 1. The average LSR velocity of stars in the Galactic Center (km s^{-1}) vs. distance from IRS 16 (pc). Only data along the Galactic plane are shown. The open circles are from observations of integrated starlight in a 0.8 pc diameter beam (McGinn *et al.* 1989). The filled circles are from observations of individual stars (Rieke and Rieke 1988a) averaged in bins of galactic longitude. Error bars are $\pm 1\ \sigma$.

rotation curve appears to peak at $r \sim 2$ pc, then turns over at $r \sim 3$ pc to much smaller values. The upper limit on rotation at $r \sim 5$ pc from the Rieke and Rieke (1988a) data is consistent with the small value of rotation derived from OH/IR stars (Winnberg *et al.* 1985; Lindqvist *et al.* 1988) over $r = 5$–100 pc. It is interesting that the maximum of the stellar rotation curve occurs in the vicinity of the circumnuclear molecular ring.

The velocity dispersion of the integrated starlight observed by McGinn *et al.* (1989) shows a definite increase within a 1 pc radius from the Galactic Center. The velocity dispersion derived from individual stellar velocities by Rieke and Rieke (1988a), while agreeing with the observations of McGinn *et al.* (1989) for $r > 1$ pc, shows no increase in dispersion at small radii. Figure 2 shows the velocity dispersion derived from Rieke and Rieke (1988a) after correcting their data for rotation compared to that of McGinn *et al.* (1989). The discrepancy at $r < 1$ pc could reflect true differences in the kinematics of the bright and fainter stars, due perhaps to a difference in the masses or ages of the bright and faint stars. However, the difference between the McGinn *et al.* (1989) observations and each of the two Rieke and Rieke (1988a) data points at $r < 1$ pc is only marginally significant (2 σ). Further observations of both integrated starlight and larger numbers of individual bright stars are needed to resolve these questions.

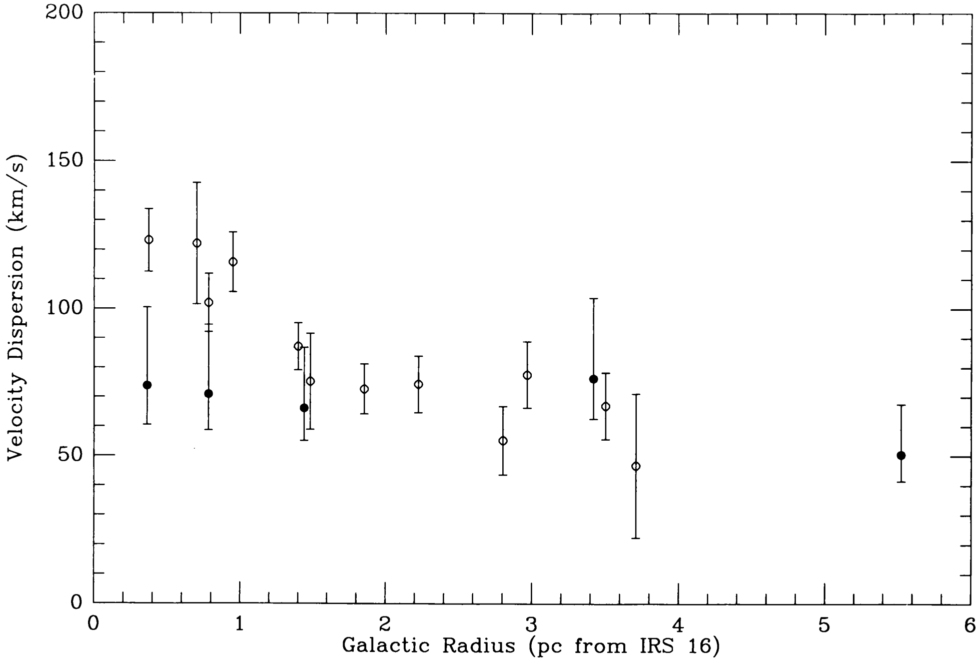

Fig. 2. The velocity dispersion of starlight in the Galactic Center (km s^{-1}) vs. radius from IRS 16 (pc). The open circles are from observations of integrated starlight in a 0.8 pc diameter beam (McGinn *et al.* 1989). The filled circles are from observations of individual stars (Rieke and Rieke 1988a), averaged in bins of galactocentric radius after correction for average rotational velocity. Error bars are ± 1 σ.

https://doi.org/10.1017/S0074180900186930 Published online by Cambridge University Press

4. The Mass Distribution

Observations of gas kinematics have been used to derive the mass distribution of the central few parsecs of the Galaxy, under the assumption that the gas motions trace the gravitational potential (Genzel and Townes 1987, and references within). However, the presence of a strong magnetic field (Aitken *et al.* 1986; Werner *et al.* 1988), shocks (Gatley *et al.* 1984, 1986), and possible high-velocity outflows (Hall, Kleinmann, and Scoville 1982; Geballe *et al.* 1984, 1987) all complicate the interpretation of the gas kinematics. Observations of stellar kinematics should provide an unambiguous measure of the gravitational potential, with the only difficulty in interpretation being the degree of anisotropy of the stellar velocity distribution.

The enclosed mass $M(r)$ at a galactocentric radius r can be derived from observations of stellar kinematics using the equation of stellar hydrodynamics. This yields

$$M(r) = \frac{r\,\sigma(r)^2}{G}\left[-\frac{d\ \ln\ n_*(r)}{d\ \ln\ r} - \frac{d\ \ln\ \sigma(r)^2}{d\ \ln\ r} + \frac{V_{ROT}(r)^2}{\sigma(r)^2} - 2\beta\right].$$

In this equation the enclosed mass depends most on $\sigma(r)$, the observed velocity dispersion. The constant of proportionality between $\sigma(r)^2$ and $M(r)$ is a sum of terms; the most important term is the gradient in the stellar density, $d\ln n_*(r)/d\ln r$, which equals α for a stellar density distribution $n_*(r) \sim r^{-\alpha}$. Observations give $\alpha = -1.8 \pm 0.1$ (Becklin and Neugebauer 1968; Allen, Hyland, and Jones 1983). Rieke and Rieke (1988a) and McGinn *et al.* (1989) find that the ratio of $V_{ROT}(r)$, the rotational velocity, to $\sigma(r)$, the velocity dispersion, is very small. Both groups also find that the radial gradient in the velocity dispersion, $d\ln\sigma(r)^2 \ / \ d\ln r$, is also small. The anisotropy parameter, β, is generally assumed to be 0. McGinn *et al.* (1989) have compared theoretical models to observations of the Galactic Center to show that β is likely to be small, but there is still some uncertainty in its value that could have an important effect on $M(r)$.

The above equation is well-suited to analysis of integrated light measurements, where the velocity dispersion is well determined at each radial position. However, for interpreting the velocities of individual bright stars, the small numbers of stars in each radius bin leads to large errors in the estimate of velocity dispersion. Bahcall and Tremaine (1981) developed a technique for deriving the best estimate, M_I, for $M(r)$ from small numbers of individual velocities:

$$M_I = \frac{16}{\pi G N}\,\Sigma\, v_i^2\, r_i,$$

where v_i is the velocity of an individual star at radius r_i, and N is the total number of stars in the sum. This mass estimator assumes that $\beta = 0$.

The total mass distribution of the Galactic Center derived by Sellgren *et al.* (1987) based on stellar kinematics is consistent with the mass distribution of the stellar cluster, with no requirement for additional dark mass in the center. This comparison assumes a small core radius and a constant M/L ratio for the cluster with radius. The Sellgren *et al.* (1987) work, however, was only based on 13 stars and thus had large uncertainties in the derived mass distribution. Rieke and Rieke (1988a), using radial velocity observations of 54 stars within a 6 pc radius of the Galactic Center, derive a total mass distribution consistent with that of Sellgren *et al.* (1987), but with much smaller uncertainties due to the larger number of stars.

The total mass distribution derived by Rieke and Rieke (1988a) from stellar kinematics is consistent with the mass distribution of the stellar cluster only if the core radius is small, i.e., 0.1 pc, as observed by Allen, Hyland, and Jones (1983). Rieke and Rieke (1988a) find, however, that the total mass distribution requires a central dark mass of $2 \times 10^6\ M_\odot$ if the core radius is instead 0.6–0.8 pc, as is observed by Rieke and Lebofsky (1987). The total mass distribution of Rieke and Rieke (1988a) is consistent with that found by McGinn *et al.* (1989), based on the stellar kinematics of the integrated starlight in the Galactic Center. McGinn *et al.* (1989) find that for core radii $\geq$0.4 pc a central dark mass of 2–4 $\times\ 10^6\ M_\odot$ is required; the derived total mass distribution is only consistent with the mass of the stellar cluster if the core radius is $\leq$0.05 pc. A comparison of the total mass distributions derived from stellar kinematics is shown in Figure 3.

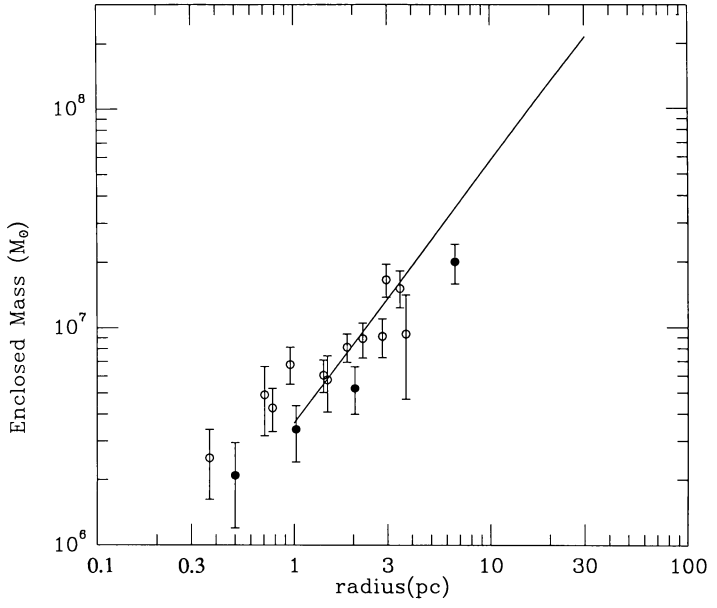

Fig. 3. Enclosed mass in the Galactic Center ($M_\odot$) vs. radius from IRS 16 (pc). The open circles are derived from kinematics of integrated starlight in a 0.8 pc diameter beam (McGinn *et al.* 1989), using the equation of stellar hydrodynamics. The filled circles are derived from kinematics of individual stars (Rieke and Rieke 1988a), assuming an isotropic velocity distribution, making no correction for average rotational velocity, and using the mass estimator of Bahcall and Tremaine (1981). Error bars are $\pm 1\ \sigma$. The solid line is the mass of the stellar cluster derived from the 2.2 μm light distribution (Sanders and Lowinger 1972), assuming $M/L = 3$.

While the kinematics of stars and gas are quite different, the mass distributions derived from each are remarkably consistent. Figure 4 shows the enclosed mass at different galactocentric radii, derived from kinematics of ionized gas, neutral and molecular gas, and stars. The stellar data from McGinn *et al.* (1989), Sellgren *et al.* (1987), and Winnberg *et al.* (1985) are shown; stellar data from Rieke and Rieke (1988a) and Lindqvist *et al.* (1988) are all consistent with the data shown. This figure emphasizes the importance of the core radius of the stellar cluster in establishing whether or not a central dark mass is required to explain the observed total mass distribution.

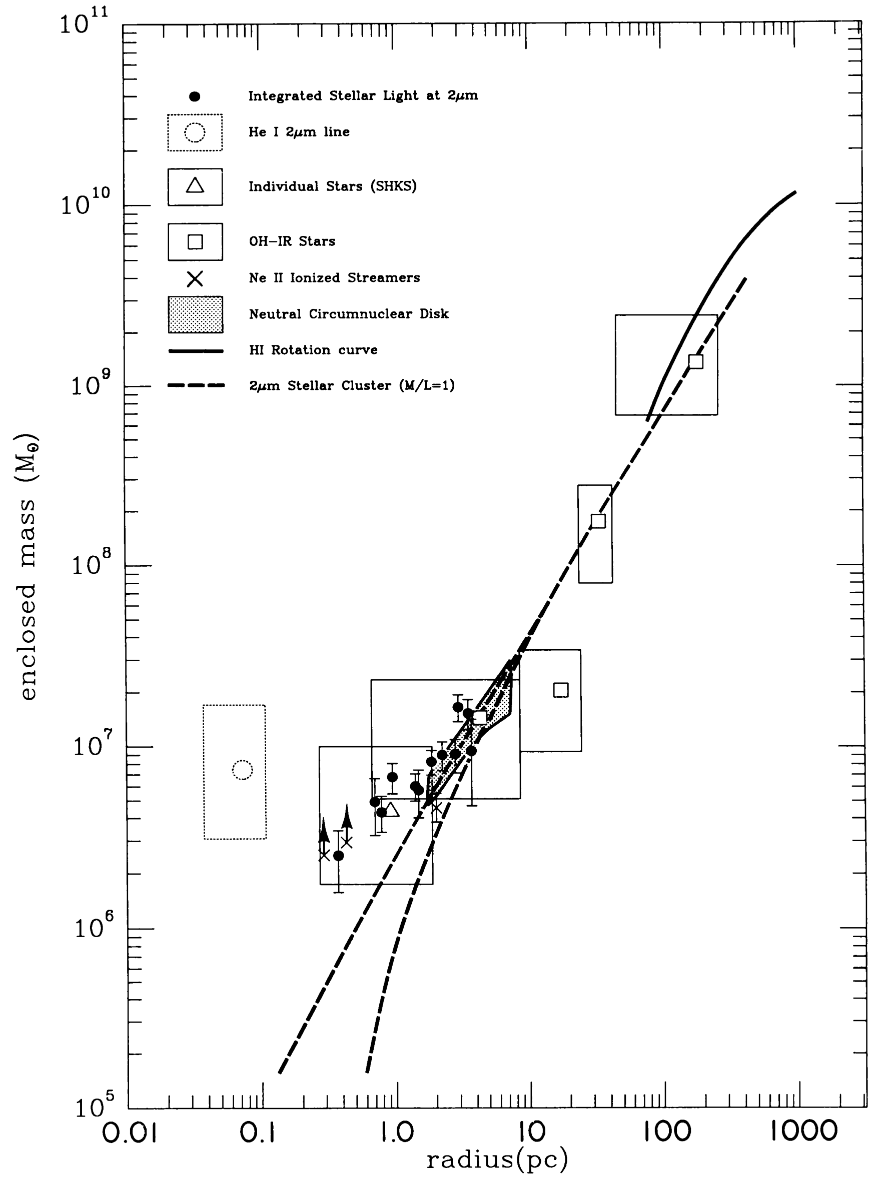

Fig. 4. Enclosed mass in the Galactic Center ($M_\odot$) vs. radius from IRS 16 (pc), from McGinn *et al.* (1989), adapted from Genzel and Townes (1987). The filled circles are derived from kinematics of integrated starlight (McGinn *et al.* 1989), while the other symbols are derived from kinematics of ionized gas, neutral gas, and OH/IR stars (Genzel and Townes 1987). The dashed lines are the mass of the stellar cluster derived from the 2.2 μm light distribution, assuming $M/L = 1$, for core radii of 0.1 and 1 pc.

5. Conclusions

Studies of the stellar cluster at the very center of our Galaxy are important not only for understanding the nature of the stars there, but also for determining whether or not star formation has recently occurred and crucial to establishing whether or not a central dark mass, such as a massive black hole, is required to explain the mass distribution of the Galactic Center. Observations of the stellar cluster have led to the following conclusions:

1. The observed surface brightness of 2 μm radiation implies a radial density of stars proportional to $r^{-1.8\pm0.1}$. This, however, does not correct for the spatially variable extinction observed and assumes a constant M/L ratio for the stars, which may not be justified.

2. The core radius of the stellar cluster is somewhere between 0.05 and 0.8 pc; the core radii of brighter and fainter stars in the cluster may be different, perhaps suggesting a change in population with radius. The choice of IRS 16 or Sgr A* as the center of the stellar cluster also has an important influence on the derived core radius. The value of the core radius is essential to establishing whether or not a central dark mass is required to explain the mass distribution.

3. The presence of the supergiant IRS 7 in the central few parsecs of the Galaxy establishes that at least one star has formed recently. The extent of and time scale for star formation in the Galactic Center is still being studied.

4. The kinematics of stars and gas are different; the gas shows predominantly systematic motion, while the stars show predominantly velocity dispersion. However, the mass distributions derived from stellar and gas kinematics are consistent. The total mass distribution derived from kinematics is consistent with the mass of the stellar cluster inferred from the 2 μm light distribution if the core radius is $\leq$0.1 pc; however, a central dark mass of 2–4 $\times$ 10^6 $M_\odot$ is required if the core radius is 0.6–0.8 pc.

6. Acknowledgments

The author thanks E. Becklin, J. Lugten, M. McGinn, and G. Rieke for useful conversations; and R. Catchpole, D. Depoy, I. Gatley, M. Lindqvist, G. Rieke, and M. Rieke for communicating results prior to publication. This research was supported by NSF grant AST-8700618. The author is supported by NASA contract NASW-3159.

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