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The Supermassive Black Hole at the Center of the Milky Way

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Abstract

Within the last year two results dramatically strengthened the case for a supermassive black hole at the center of the Milky Way and our understanding the black hole's effect on its environment. First, orbital solutions for multiple stars have been obtained, using adaptive optics and speckle imaging to study the motions of stars in the plane of sky over the past decade. The three most remarkable orbits are those of the newly identified stars S0-16, which passed a mere 60 AU from the central dark mass at a velocity of 9,000 km s^{-1} in 2000, and S0-19, which at one time was posited to be the near-infrared counterpart to Sgr A*, and the previously recognized S0-2, which has an orbital period of a mere 16 years. A simultaneous orbital analysis yields the most accurate and precise values of the location and mass of the Galaxy's central dark matter. The location is consistent with the inferred infrared position of Sgr A* but with an uncertainty that is a factor of 7 smaller (± 1.5 milliarcsec). The estimated mass from orbital motion is $3.7(\pm0.4) \times 10^6 (\frac{R_0}{8\,\mathrm{kpc}})^3 M_\odot$ and is a more direct measure of mass than that obtained from velocity dispersion measurements, which are as much as a factor of 2 times smaller; this brings the Milky Way into better agreement with the $M_\bullet - \sigma$ relationship. Furthermore, by confining the mass to within a radius of a mere 0.0003 pc or 1,000 R_{Sch}, this orbital analysis increases the inferred dark mass density by four orders of magnitude compared to earlier analyses based on velocity and acceleration vectors, making the Milky Way the strongest existing case for a supermassive black hole at the center of any normal type galaxy.

Second, with the introduction of an adaptive-optics-fed spectrometer, the first detection of spectral absorption lines in one of the high-velocity stars, S0-2, was obtained one month after its closest approach to the Galaxy's central supermassive black hole. Both Br γ λ2.1661 μm and He I λ2.1126 μm are seen in absorption with equivalent widths and an inferred stellar rotational velocity that are consistent with that of an O8-B0 dwarf, which suggests that S0-2 is a massive ($\sim$15 $M_\odot$), young ($<$10 Myr) main-sequence star. Similarly, the lack of CO detected in several of the other high-velocity stars suggests that they are also young. This presents a major challenge to star formation theories, given the strong tidal forces that prevail over all distances reached by these stars in their current orbits and the difficulty in migrating these stars inward during their lifetime from farther out where tidal forces should no longer preclude star formation.

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1.1 Introduction

While the Milky Way was neither the first nor the most obvious place to search for a supermassive black hole, the case for one at the center of the Galaxy is quickly becoming the most iron clad. The first hint of a central concentration of dark matter came from radial velocity measurements of ionized gas located in a three-armed structure known as the mini-spiral, which extends from the center out to about 1–2 pc (Lacy et al. 1980). Concerns that the gases' motions were not tracing the gravitational potential were quickly allayed by radial velocity measurements of stars, which are not susceptible to nongravitational forces (McGinn et al. 1989; Haller et al. 1996; Genzel et al. 1997). These early dynamical measurements of the gas and stars suggested the presence of $3 \times 10^6 M_\odot$ of dark matter and confined it to within a radius of $\sim$0.1 pc. The implied dark matter density was not sufficiently high to definitively claim this as evidence for a single supermassive black hole, since the measurements imposed a lifetime for clusters of dark objects that was not significantly shorter than the age of the Galaxy (Maoz 1998). To make further progress in understanding the underlying source of dark matter at the center of the Galaxy, it was necessary to use techniques that compensated for the distorting effects of the Earth's atmosphere, which had restricted the earlier studies of the dark matter distribution to radii of 0.1 pc or larger.

In the early- to mid-1990's, two independent groups initiated 2 μm high spatial resolution imaging studies of the central stellar cluster to measure the motions of stars in the plane of the sky. In 1992, the ESO team began their program using speckle imaging at the 3.6 m NTT and in 2002 have moved to the adaptive optics system on the 8 m VLT. The Keck team initiated their program using speckle imaging on the 10 m Keck I telescope in 1995 and began using adaptive optics on the 10 m Keck II telescope in 1999. The first phase of these experiments yielded proper motion velocities, which increased the implied dark matter density by 3 orders of magnitude to $10^{12} M_\odot/\mathrm{pc}^3$ (Eckart & Genzel 1997; Ghez et al. 1998). This eliminated a cluster of dark objects, such as neutron stars or stellar mass black holes, as a possible explanation of the Galaxy's central dark mass concentration (Maoz 1998) and left only the fermion ball hypothesis (e.g., Tsiklauri & Viollier 1998; Munyaneza & Viollier 2002) as an alternative to a single supermassive black hole. The velocity dispersion measurements also localized the dark matter to $\pm$100 mas (4 milli-pc) at a position consistent with the nominal location of the unusual radio source Sgr A* (Ghez et al. 1998), whose emission is posited to arise from accretion onto a central supermassive black hole (e.g., Lo et al. 1985). The proper motion experiments proceeded to strengthen both the case for a supermassive black hole and its association with Sgr A* with the detection of acceleration for three stars — S0-1, S0-2, and S0-4 — which increased the dark matter density to $10^{13} M_\odot/\mathrm{pc}^3$ and positional accuracy to $\pm$30 mas (Ghez et al. 2000; Eckart et al. 2002). These experiments also revealed that the orbital periods for S0-2 and S0-1 could be as short as 15 and 35 years, respectively, which would open a new arena for dynamical studies of the central stellar cluster.

This paper summarizes the recent progress that has been made in this field on two fronts. First, with approximately a decade of proper motion measurements, is the derivation of complete 3-dimensional orbits for multiple stars that are making close approaches to the supermassive black hole at the center of the Milky Way. Second is the measurement of spectral lines in one of these high-velocity stars. These two steps forward make the strongest case yet for the presence of a supermassive black hole at the center of the Galaxy and, for the first time, allow us to take an in-depth look at the question of where these stars formed.

1.2 Proper Motion Measurements

Diffraction limited near-infrared imaging programs have published significant proper motions (S/N > 5) for 18 stars, which are located within 3$''$ of Sgr A* (Eckart & Genzel 1997; Ghez et al. 1998; Genzel et al. 2000). An additional ∼80 stars have reported proper motion values, although ∼50 of these have S/N < 3 and thus should be considered upper limits. Since the last reporting of stellar proper motions, significant progress has been made. The velocity estimates have been improved as more data have been taken, which has increased the time baseline of these studies by factors of 3.5 and 1.4 for the Keck and ESO programs, respectively. This has allowed proper motion velocity uncertainties of ∼15 km s^{-1} to be obtained for the Keck data set. Furthermore, the sensitivity to additional proper motion sources also has been improved, due, in the case of the Keck program, to three separate factors. First, the original approach was conservative in an effort to avoid falsely identifying high-velocity stars on the basis of the three maps, each of which is separated by a full year (obtained in 1995, 1996, and 1997). With multiple observations each year beginning in 1998, it was clear that many real sources were not being identified, leading to a decrease in the choice of threshold used to identify sources. Second, in 1998 it became possible to calibrate the alignment of the Keck telescope's mirror segments on NIRC, the Keck I facility infrared camera, allowing the telescope to be calibrated during the observing run at the elevation of the Galactic Center, thereby improving the image quality of the speckle maps. Lastly, beginning in 1999 adaptive optics images have been obtained, which increased the sensitivity to fainter sources. Within the central $1'' \times 1''$ ($R = 0.''5$)* alone, the number of proper motion sources has quadrupled (Ghez et al. 2004). In this review, we focus on six of the most dynamically important proper motion stars, of which three are new (S0-16, S0-19, and S0-20) and three were previously known (S0-1, S0-2, and S0-4). Figure 1.1 identifies these sources in a cleaned image from 2001, and Figure 1.2 shows their proper motions.

In terms of source confusion, S0-19 is of particular note. Its large proper motion has caused it to be misidentified in earlier papers. While it was detected by Ghez et al. (1998) in 1995 as a K = 14.0 mag source, two possible counterparts were identified in 1996. With limited time coverage, it was not possible to definitively identify either as the correct counterpart, and it was not included in the proper motion sample. The same source was reported as S3 (K = 15 mag) moving westward by Eckart & Genzel (1997) and Genzel et al. (2000). Genzel et al. (1997) report the detection of an apparently new source, S12 ($K \approx 15$ mag), in their 1996.43 image, located ∼$0.''1$ W from S3 and proposed it as the best candidate for the infrared counterpart of the compact radio source Sgr A*. This has been used in several recent papers to constrain models of Sgr A*'s flared state (e.g., Narayan 2002). In Ghez et al. (2003b,c), it is clear that S12 is simply a high velocity star that was coincident with Sgr A* in 1996, which we label S0-19. The discrepancy in magnitudes arises from the difficulties of carrying out accurate photometry in such a crowded region. This source illustrates the challenges associated with making a definitive detection of infrared emission associated with Sgr A*, given the high stellar densities and velocities and modest stellar intensity variations in this region (see Hornstein et al. 2002 for a detailed discussion of near-infrared limits on Sgr A*).

The naming convention used here was introduced by Ghez et al. (1998) and was designed to directly convey relevant information about the location of the source relative to the posi-

* Both proper motion studies cover regions that are significantly larger than $1'' \times 1''$.

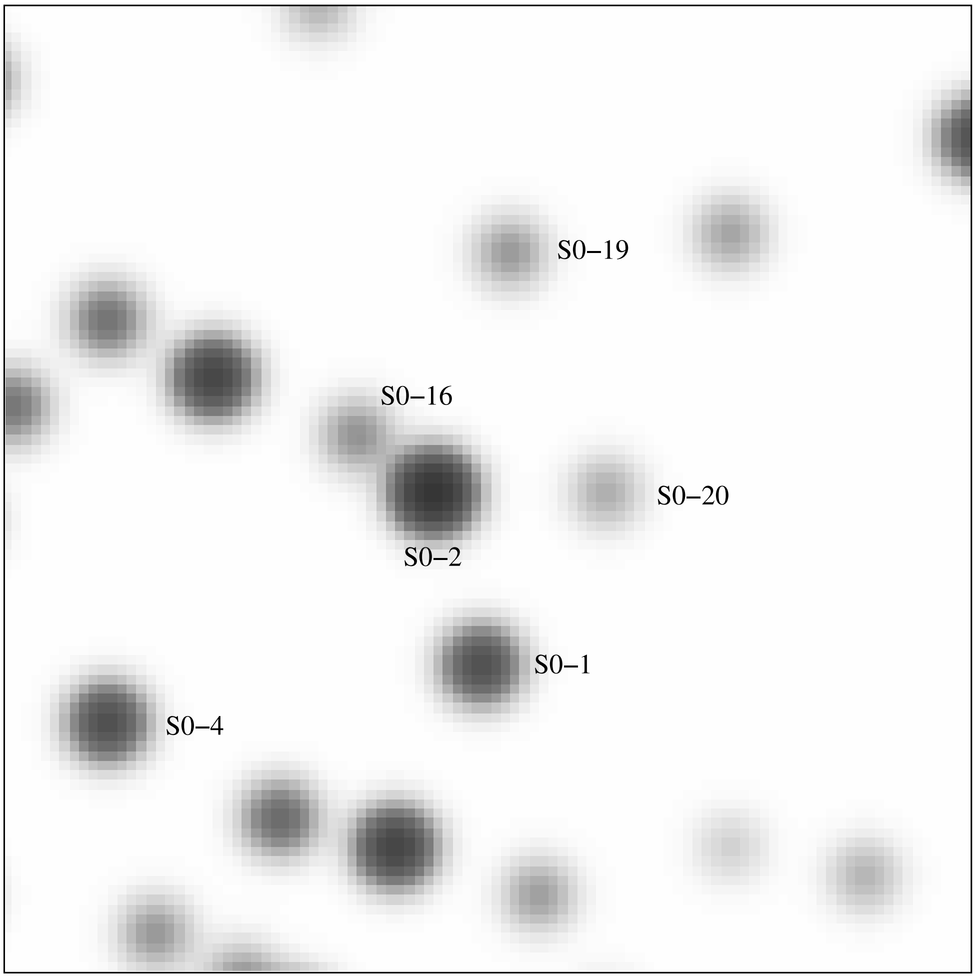

Fig. 1.1. A $1'' \times 1''$ cleaned image centered on the nominal position of Sgr A* showing the 2001 positions of some of the stars that have been followed over the course of the Keck proper motion study. Three of the newly identified stars are S0-16, S0-19, and S0-20.

tion of Sgr A*. Originally the Sgr A* position given by Menten et al. (1997) was adopted, and the surrounding field was divided into concentric arcsecond-wide annuli centered on Sgr A*. Stars lying within the central circle, which has radius $1''$, were given names S0-1, S0-2, S0-3, etc. Stars lying in the annulus between radii of $1''$ to $2''$ were given the names S1-1, S1-2, and so on. The number immediately following "S" thus refers to the inner radius of the annulus in which the star lies. The number following the hyphen was ordered in the sense of increasing distance from Sgr A* within each annulus. In this scheme, newly identified sources are named by incrementing the number following the hyphen within each annulus and ordered in the sense of increasing distance from Sgr A*. Since the original list within $1''$ ended at 15, the newly identified stars begin with 16. S0-16, S0-17, and S0-18 were labeled by Gezari et al. (2002), and S0-19 and S0-20 were first presented at the Rees Symposium

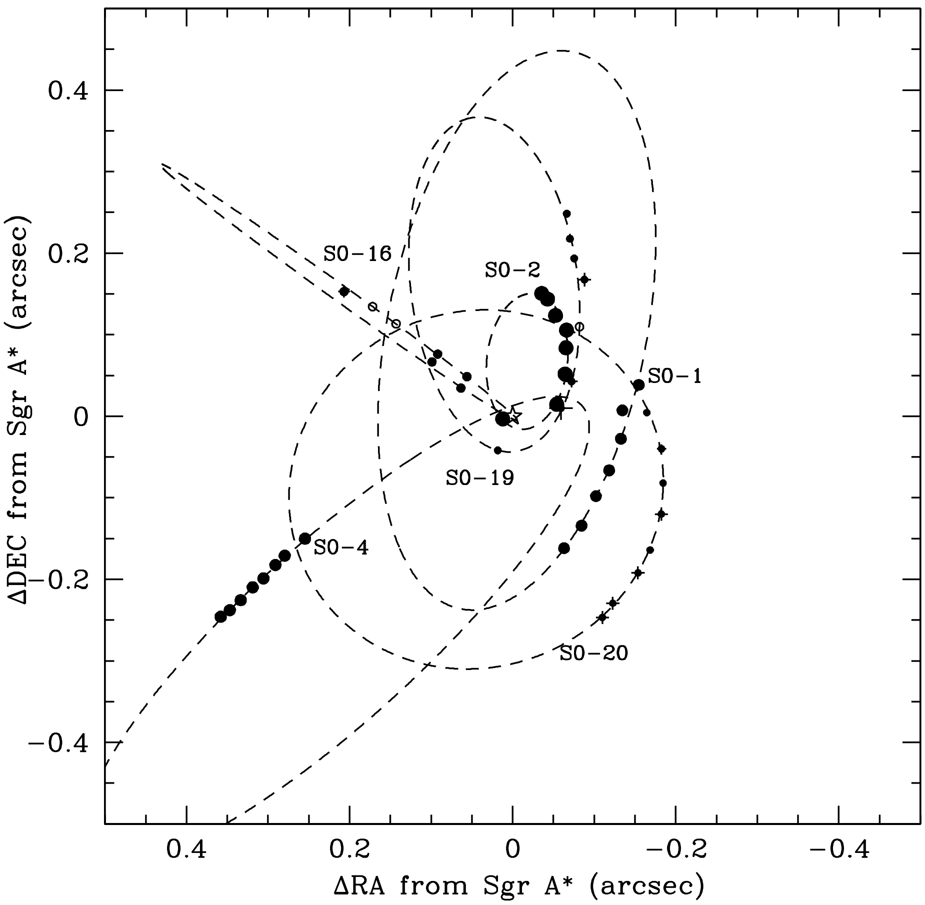

Fig. 1.2. The annual positions of the stars labeled in Fig. 1.1, which have orbital solutions. While several measurements are obtained each year and are critical to the orbital fits at the time of closest approach, the use of annual averages helps to depict the passage of time in this figure. Each star is labeled near its first measurement. (Adapted from Ghez et al. 2004.)

"Making Light of Gravity," held in Cambridge, England (July 2002). Due to the motions of stars, the current distance rank does not necessarily match the one at the time of discovery.

1.3 Spectral Line Measurements

In 2002, the high proper motion star, S0-2, was observed with NIRC2, the W. M. Keck II 10 m telescope facility near-infrared adaptive-optics instrument (Matthews et al. 2004) in a mode that achieved a spectral resolution of $R \approx 4{,}000$ (~ 75 km s^{-1}). The resulting spectrum of S0-2, shown in Figure 1.3, has two identifiable spectral lines. These are both seen in absorption and are identified as the H I (4-7) or Brγ line at 2.166 μm and the He I triplet at 2.1126 μm ($3p\,^3P^0 - 4s\,^3S$), which is a blend of three transitions at 2.11274,

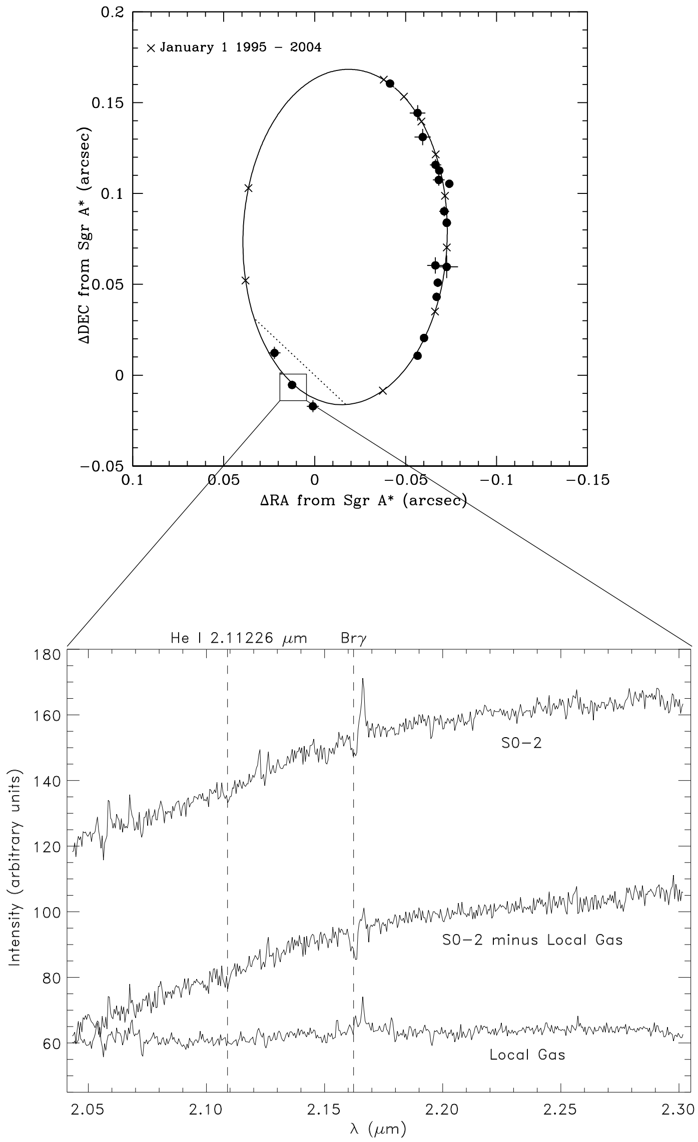

Fig. 1.3. In the lower panel is the first spectrum of S0-2 to show detectable photospheric absorption lines (Brγ and He I λ2.1126 μm). The final spectrum (middle) is the raw spectrum (top; with only an instrumental background removed) minus a local sky (bottom). The horizontal dimension has been re-binned by a factor of two for display purposes only. The vertical lines are drawn at 2.10878 and 2.16230 μm, which correspond to the locations of Brγ and He I for a $V_{\rm LSR}$ of -513 km s^{-1}. This spectrum was obtained in 2000 June at the same time as one of the proper motion measurements shown in the upper panel (filled circles). The crosses in the upper panel mark January 1 of each year between 1995 and 2004 for the best-fit orbit solution (solid line), which is based on both the radial velocity and proper motions. The dotted line is the line of nodes, which reveals S0-2 to be behind the black hole for a mere $\sim$0.5 years out of its 15-year orbit. (Adapted from Ghez et al. 2003a.)

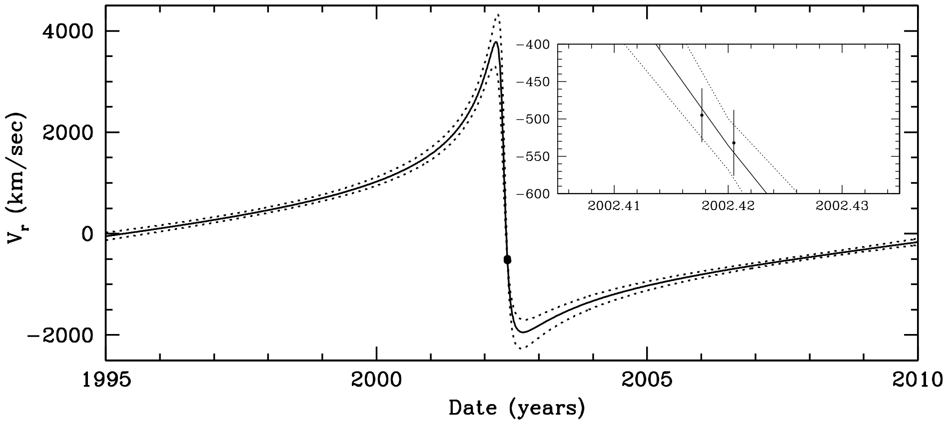

Fig. 1.4. Measured radial velocities along with predicted radial velocities. The solid curve comes from the best-fit orbit and the dotted curves display the range for the orbital solutions allowed with the present data sets, which include two radial velocity measurements separated by one night. The inset panel shows a detailed view of the plot centered on the two observations, which differ by 40 km s^{-1}. (Adapted from Ghez et al. 2003a.)

2.11267, and 2.11258 μm. The detailed properties of these two lines, which are obtained by fitting the background continuum over the whole spectrum with a low-order polynomial and fitting the lines with a Gaussian profile, are reported in Ghez et al. (2003a).

1.4 Discussion

1.4.1 Dynamics

Strong deviations from linear motions on the plane of the sky are observed for several stars that come within $0.''2$ of Sgr A*, allowing detailed orbital solutions to be carried out. The first orbital solutions reported by Ghez et al. (2000) and Eckart et al. (2002) for S0-1, S0-2, and S0-4, have the following assumptions made about the central dark mass: (1) it is confined to a point source, (2) its distance is 8 kpc (Reid 1993), (3) it has no significant velocity with respect to the Galaxy, which is supported by the lack of motion detected for Sgr A* by Reid et al. (1999) and Reid (2003) in the plane of the sky (<7 km s^{-1}), (4) its position (x_0 and y_0; the center of attraction) is coincident with Sgr A*, and (5) it has a mass $M = 2.6 \times 10^6 M_\odot$, based on velocity dispersion measurements reported by Genzel et al. (1997) and Ghez et al. (1998). This leaves six classical binary star parameters to be solved for from the proper motion data: period P^*, eccentricity e, time of periapse passage T_0, angle of nodes to periapse ω, angle of the line of nodes Ω, and inclination i. This is a well-determined problem as soon as acceleration is well measured.

Since these initial orbital estimates, more significant curvature in the proper motions of the stars has been detected, allowing less constrained orbital solutions to be obtained. For the

* With M fixed, semi-major axis A is not an independent variable.

brightest star in the central stellar cluster, S0-2†, Schödel et al. (2002) add one additional parameter to the orbit fit, by dropping the mass assumption, and derive a central mass of $3.7(\pm1.5) \times 10^6 M_\odot$. For the same star, Ghez et al. (2003a) drop both the mass and center of attraction assumptions and find a central mass that is consistent with that reported by Schödel et al. and, despite the two additional free parameters introduced by fitting for the center of attraction, obtain uncertainties of the orbital parameters that are reduced by a factor of 2–3‡.

Inclusion of radial velocity measurements for S0-2 presented by Ghez et al. (2003a) breaks the ambiguity in the inclination angle. With proper motion data alone, only the absolute value of the inclination angle can be determined, leaving the questions of the direction of revolution and when the star is located behind the black hole unresolved. Radial velocity measurements (see Fig. 1.4) indicate a negative inclination angle and consequently that S0-2 is both counter-revolving against the Galaxy and behind the black hole at the time of periapse. The improved location of the center of attraction from the orbital analysis results in a minimum offset of S0-2 from the black hole in the plane of the sky of 11 ± 2 milliarcsec, which is significantly larger than the expected Einstein radius ($\theta_E = 0.42$ milliarcsec, for the S0-2 distance behind the black hole of $\sim$ 100 AU) and therefore makes gravitational lensing an unlikely event (Wardle & Yusef-Zadeh 1992; Jaroszyński 1998a; Alexander & Loeb 2001).

In addition to S0-2, both S0-16 and S0-19 have sufficient curvature to be fit independently with a nine-parameter binary model, with the requirement that the total mass be determined with a S/N greater than 3 (Ghez et al. 2003b,c). The existence of multiple orbits is important for testing the initial assumption that the central dark mass is well modeled by a point source. Measurement of significant curvature in only one star may be equivalently well modeled by a point source and an extended mass distribution. This ambiguity can be easily understood by considering the case of a constant mass density distribution, which has closed elliptical orbit solutions but has the center of attraction located at the ellipse's center rather than at one of its focii (Binney & Tremaine 1987). The agreement between the center of attractions (Fig. 1.5) and total mass (Table 1.1 and Fig. 1.6) for these three independent orbit fits supports the use of a Keplerian orbit model, suggesting that it would be valid to assume a common center of attraction and central mass.

Fitting the orbital motions of these stars simultaneously with a common center of attraction and central mass yields more precise values than those obtained from the independent orbits. Compared to the nominal infrared position of Sgr A*, the new estimate of the center of attraction is a factor of 7 more precise (±1.5 milliarcsec) and located within the uncertainties of the former. The central dark mass is estimated to be $3.7(\pm0.4) \times 10^6 (\frac{R_0}{8\,\mathrm{kpc}})^3 M_\odot$. This mass is somewhat higher than that inferred from the velocity dispersion measurements; in particular, it is a factor of 2 higher than that estimated by a nonparametric approach presented by Chakrabarty & Saha (2001) and somewhat less discrepant with the parametric approaches (e.g., Ghez et al. 1998; Genzel et al. 2000). In principle, the difference could provide a handle on the level of anisotropy and the number density distribution of the central cluster (Genzel et al. 2000). However, it is worth recalling that the majority of velocity estimates are in fact limits (see earlier discussion of proper motion measurements), which

† S0-2 is referred to as S2 by Schödel et al. (2002).

‡ The smaller orbital parameter uncertainties are primarily due to the higher astrometric accuracy of the Keck data set, rather than the inclusion of a radial velocity measurement.

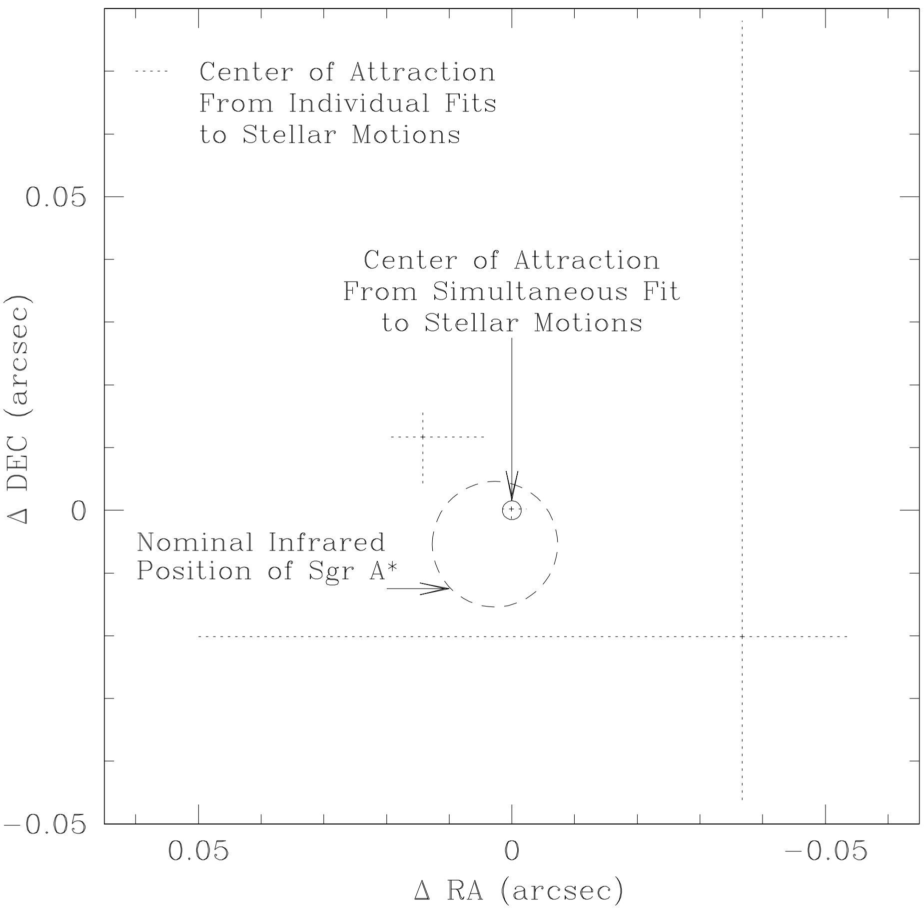

Fig. 1.5. The locations of the center of attraction from the orbital analysis of the proper motion data sets. The three independent orbits for S0-2, S0-16, and S0-19 yield consistent locations, which suggests that the central mass can indeed be modeled as a point source. A simultaneous fit to all three stars pinpoints the Galaxy's dynamical center to a location that is consistent with the nominal infrared position of Sgr A*, but with an uncertainty of a mere 1.5 milliarcsec. All positions are shown with 1 σ uncertainties.

means that the intrinsic velocity dispersion can be altered significantly if the uncertainties are not well estimated (this affects the bias term that has to be removed) and are a strong function of how the data set is weighted. This discrepancy should therefore not be used to infer properties of the central stellar cluster and the more robust dynamical mass should be used in future characterizations of the Galaxy's central dark mass.

Orbital analysis dramatically raises estimates of the dark matter density. Since this mass is confined to radii less than the minimum periapse passage of any of the stars included in the orbital fit (set by S0-16 at 60 AU = 0.0003 pc), the lower limit on the central dark

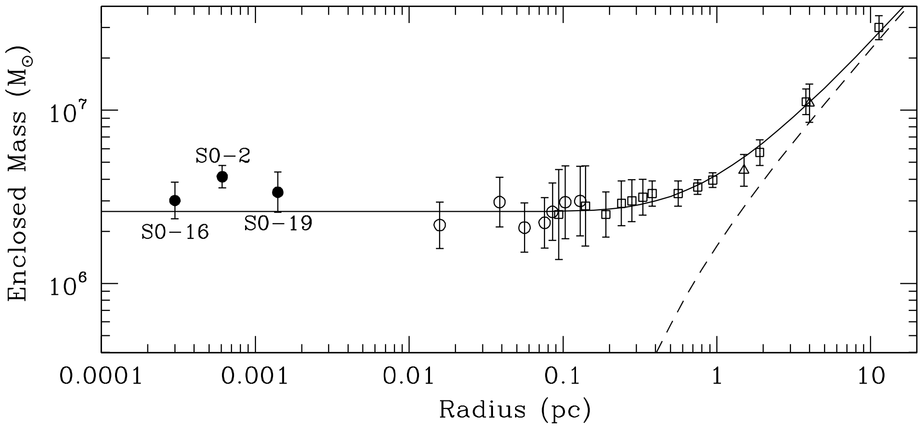

Fig. 1.6. Enclosed mass as a function of radius. The masses from the individual stars' orbital motion agree with one another. The solid line shows the best-fit black hole plus luminous cluster model based on the earlier measurements. While the new mass estimates from the orbital analysis are systematically higher than earlier estimates from velocity dispersion measurements, this difference is most likely primarily due to the way velocity dispersion uncertainties are treated. The new orbital masses increase the central dark mass density by 4 orders of magnitude, dramatically strengthening the case for a central supermassive black hole.

mass density is increased to $3 \times 10^{16} M_\odot/\mathrm{pc}^3$, 3 orders of magnitude larger than previous estimates from measurements of acceleration vectors (Ghez et al. 1998). and 4 orders of magnitude larger than that based on velocity vectors (Genzel et al. 1997, 2000; Ghez et al. 1998). Although previous density estimates were sufficient to rule out the possibility of a cluster of dark objects based on evaporation and collisional lifetimes (Maoz 1998), the present observations dramatically strengthen this argument. At these densities, such a cluster of dark objects would have a lifetime of less than 10^5 years, which is significantly shorter than the age of the Galaxy, making this a highly unlikely scenario. Likewise, the fermion ball hypothesis becomes less tenable (Viollier 2003). For the Galactic Center, it is still possible to make this scenario work by increasing the particle mass to 50 kev c^{-2}; however, this object is unlikely to survive for very long before becoming a black hole. More generally, these new observations impose a maximum mass for a fermion ball of $2 \times 10^8 M_\odot$, which is less massive than the most massive central dark concentrations found in other galaxies and therefore indicates that fermion balls are no longer viable alternatives to all cases of supermassive black holes. With the central dark mass now confined to a radius equivalent to $1{,}000 \times$ the Schwarzschild radius, the orbits present the strongest case yet for a supermassive black hole at the center of the Milky Way galaxy and, more broadly, at the center of any normal type galaxy.

Table 1.1. *Estimates of the central dark mass from fits to the stellar orbital motion. The reported values come from fits that assume a distance of 8 kpc. For the Keck results, only solutions with fractional uncertainties less than 30% are listed here.*

Star	Mass ($10^6 M_\odot$)	Reference
S0-2	3.7 ± 1.5	Schödel et al. (2002)
	4.1 ± 0.6	Ghez et al. (2003a)
S0-16	3.0 ± 0.7	Ghez et al. (2004)
S0-19	3.4 ± 0.9	Ghez et al. (2004)
Simultaneous	3.7 ± 0.4	Ghez et al. (2004)

1.4.2 Stellar Astrophysics

The detection of absorption lines by Ghez et al. (2003a) allows the ambiguities in spectral classification, which are present when only photometric information is available, to be sorted out. The average brightness at 2.2 μm for S0-2 is $K \approx 13.9$ mag and there is no evidence of brightening during or after periapse passage (Ghez et al.). With a distance of 8.0 kpc and K-band extinction of 3.3 mag (Rieke, Rieke, & Paul 1989), the 2.2 μm brightness of S0-2 implies that, if it is an ordinary star unaltered by its environment, it could either be an O9 main-sequence star or a K5 giant star; all supergiants are ruled out since they are too bright by at least 2 magnitudes in the K band. Kleinmann & Hall (1986) provide a 2.0–2.5 μm spectral atlas of late-type stars that demonstrates that if S0-2 is a K5 giant star, then it should have deep CO absorption lines, which definitively were not detected in either this experiment or in our earlier experiment reported by Gezari et al. (2002). In contrast, the spectral atlas of 180 O and B stars constructed by Hanson, Conti, & Rieke (1996) shows that an O9 main-sequence star both lacks the CO absorption and has Br γ and He I $\lambda 2.1126$ μm consistent with the observed values. Furthermore, stars in this comparison sample earlier than O8 show N III $\lambda 2.115$ μm in emission and He II $\lambda 2.1885$ μm in absorption above our 3 σ thresholds; the lack of photospheric He I $\lambda 2.058$ μm absorption does not provide any additional constraints. Similarly, dwarf B-type stars later than B0 have absorption-line equivalent widths that are too large. Together, photometry and absorption-line equivalent widths permit dwarf spectral types ranging from O8 to B0. Likewise, the rotational velocity of 224 km s^{-1} is reasonable for this range (Gathier, Lamers, & Snow 1981). S0-2, therefore, appears to have a spectral type, and hence temperature ($\sim$30,000 K), as well as luminosity ($\sim 10^3$ $L_\odot$) that are consistent with a main-sequence star having a mass of $\sim$15 $M_\odot$ and an age $<$10 Myr.

It is challenging to explain the presence of such a young star in close proximity to a supermassive black hole. Assuming the black hole has not significantly affected S0-2's appearance or evolution, S0-2 must be younger than 10 Myr and thus formed relatively recently. If it has not experienced significant orbital evolution, its apoapse distances of $\sim$2,000 AU implies that star formation is possible in spite of the tremendous tidal forces presented by the black hole, which is highly unlikely. If this star formed at larger distances from the black hole and migrated inward, then the migration would have to be through a very efficient process. Current understanding of the distribution of stars, however, does not permit such efficient migration. This problem is similar to that raised by the He I emission-line stars (e.g., Sanders 1992, 1998; Morris 1993; Morris, Ghez, & Becklin 1999; Gerhard 2001; Kim & Morris 2004), which are also counter-revolving around the Galaxy (Genzel et al. 1997), but amplifies it with a distance from the black hole that is an order of magnitude smaller. Several other stars in the central $1'' \times 1''$, which collectively are known as the Sgr A* stellar cluster are likely to be similarly young, given their 2 μm luminosities and lack of CO absorption in spectra of individual stars (Genzel et al. 1997; Gezari et al. 2002) as well as in integrated spectra of the Sgr A* stellar cluster (Eckart, Ott, & Genzel 1999; Figer et al. 2000). Gould & Quillen (2003) recently suggested that these stars might be the captured companions from massive binary stars that fortuitously made a nearby encounter with the central black hole. An alternative explanation for these hot photospheres is that they may be significantly altered by their environment. While their periapse passage are too large for them to be tidally heated by the black hole, as explored by Alexander & Morris (2003), they may be affected by the high stellar densities found in this region. On the one hand, the high stellar densities might allow them to be older giant stars that have had their outer atmosphere stripped through collisions; however, to generate the necessary luminosity, significant external heating is required (Alexander 1999). On the other hand, high stellar densities might lead to a cascade of merger events (Lee 1996), which would allow these stars' formation process to have begun more than 10 Myr ago. However, a large number of collisions would have had to occur to provide the necessary lifetime to bring it in from sufficiently large radii. More exotically, it could be a "reborn" star, which occurs as the product of a merger of a stellar remnant with a normal star. None of these possibilities are altogether satisfactory, leaving the Sgr A* cluster stars as a paradox of apparent youth in the vicinity of a supermassive black hole.

1.5 Conclusions

After roughly a decade of high-spatial resolution imaging, the first three-dimensional orbital motion solutions have been obtained for several stars. For three of these stars, the orbital mass uncertainties are less than 30%. These measurements confine the central dark mass to within a radius of a mere 60 AU, or equivalently 1,000 $R_{\rm Sch}$, dramatically strengthening the case for a supermassive black hole, whose location is now determined to within $\pm$ 1.5 milliarcsec.

The precision of the proper motion and radial velocity measurements opens up additional new realms for dynamical studies in the Galactic Center. First is the possibility of obtaining a direct measure of the distance to the Galactic Center, R_0, from orbital fits (Salim & Gould 1999; Ghez et al. 2003a). The existing radial velocity measurements were obtained just 30 days after the star's closest approach to the black hole when the radial velocity was changing very rapidly (see Fig. 1.4), which, along with the proper motion measurements, constrains $M/R_0{}^3$ very effectively ($\sim$15% uncertainty), but does not yet produce a meaningful measurement of R_0. Nonetheless, as Figure 1.4 shows, the radial velocities from the currently allowed orbits quickly diverge, producing a spread of a few hundred km s^{-1} in one year. With one more year of radial velocity measurements, the orbital fits based on both proper motions and additional radial velocity measurements should provide the most direct and precise estimate of the distance to the Galactic Center.

A second opportunity is the possibility of detecting deviations from a Keplerian orbit.

These might arise from precession of the periapse distance due to general relativistic effects (Jaroszyński 1998b; Fragile & Matthews 2000)* or an extended mass distribution (Rubilar & Eckart 2001), in the form of either an entourage of stellar remnants surrounding the central supermassive black hole, a spike of dark matter particles (Gondolo & Silk 1999; Ullio, Zhao, & Kamionkowski 2001), or a binary black hole.

While the Milky Way has become one of the most convincing cases of a supermassive black hole, it is one of the least massive. It therefore potentially has an important role to play in estimates of the $M_\bullet - \sigma$ relation (Ferrarese & Merrit 2000; Gebhardt et al. 2000)*. The higher mass value from the orbits brings our Galaxy into better agreement with the $M_\bullet - \sigma$ relationship derived from a large sample of galaxies.

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* This would require the discovery of a star with a significantly smaller periapse passage.
* The current impact of the Milky Way on the $M_\bullet - \sigma$ relation, however, is limited by uncertainties in the determination of the integrated bulge velocity dispersion.

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