A Giant Step: from Milli- to Micro-arcsecond Astrometry
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Probing the properties of the Milky Way's central supermassive black hole with stellar orbits

A. M. Ghez[1], S. Salim[1,3], N. Weinberg[2,4], J. Lu[1], T. Do[1], J. K. Dunn[1], K. Matthews[3], M. Morris[1], S. Yelda[1], E. E. Becklin[1]

[1]UCLA Department of Physics and Astronomy
Los Angeles, CA 90095-1547 USA
email: ghez, jlu, tdo, jkdunn, morris, syelda, becklin@astro.ucla.edu

[2]California Institute of Technology, Pasadena, CA 91125 USA
email: kym@caltech.edu

[3]NOAO, 950 N Cherry Ave, Tucson, AZ 85719 USA
email: samir@noao.edu

[4]University of California Berkeley, Department of Astronomy
Berkeley, CA 94720-3411 USA
email: nnw@astron.berkeley.edu

Abstract. We report new precision measurements of the properties of our Galaxy's supermassive black hole. Based on astrometric (1995-2007) and radial velocity (2000-2007) measurements from the W. M. Keck 10 meter telescopes, the Keplerian orbital parameters for the short period star S0-2 imply a distance of 8.3 ± 0.3 kpc, an enclosed mass of $4.8 \pm 0.3 \times 10^6 M_\odot$, and a black hole position that is localized to within ± 1 mas and that is consistent with the position of SgrA*-IR. Astrometric bias from source confusion is identified as a significant source of systematic error and is accounted for in this study. Our black hole mass and distance are significantly higher than previous estimates. The higher mass estimate brings the Galaxy into better agreement with the relationship between the mass of the central black hole and the velocity dispersion of the host galaxy's bulge observed for nearby galaxies. It also raises the orbital period of the innermost stable orbit of a non-spinning black hole to 38 min and increases the Rauch-Tremaine resonant relaxation timescales for stars in the vicinity of the central black hole. Taking the black hole's distance as a measure of R_0, which is a fundamental scale for our Galaxy, and other measurements of galactic constants, we infer a value of the Galaxy's local rotation speed (θ_0) of 255 ± 13 km s^{-1}. With the precisions of the astrometric and radial velocity measurements that are now possible with Laser Guide Star Adaptive Optics, we expect to be able to measure Ro to an accuracy of ∼1%, within the next ten years, which could considerably reduce the uncertainty in the cosmological distance ladder.

Keywords. Galaxy: center, Galaxy: fundamental parameters, Galaxy: kinematics and dynamics, techniques: high angular resolution, stars: distances

1. Introduction

Ever since the discovery of fast moving (v > 1000 km s^{-1}) stars within 0.″3 (0.01 pc) of our Galaxy's central supermassive black hole (Eckart & Genzel 1997; Ghez *et al.* 1998), the prospect of using stellar orbits to make precision measurements of the black hole's mass (M_{bh}) and kinematics, the distance to the Galactic center (R_0) and, more ambitiously, to measure post-Newtonian effects has been anticipated (Jaroszynski 1998, 1999; Salim & Gould 1999; Fragile & Mathews 2000; Rubilar & Eckart 2001; Weinberg, Milosavlejic & Ghez 2005; Zucker & Alexander 2007). An accurate measurement of the

Galaxy's central black hole mass is useful for putting the Milky Way in context with other galaxies through the apparent relationship between the mass of the central black hole and the velocity dispersion, σ, of the host galaxy's bulge (e.g., Ferrarese & Merrit 2000; Gebhardt *et al.* 2000; Tremaine *et al.* 2002). It can also be used as a test of this scaling, as the Milky Way has the most convincing case for a supermassive black hole of any galaxy used to define this relationship. Accurate estimates of R_0 impact a wide range of issues associated with the mass and structure of the Milky Way, including possible constraints on the shape of the dark matter halo and, in comparison with future precision measurements of R_0 from tidal debris streams, the possibility that the Milky Way is a lopsided spiral (e.g., Reid 1993; Olling & Merrifield 2000; Majewski *et al.* 2006). Furthermore, if measured with sufficient accuracy ($\sim$1%), the distance to the Galactic center could influence the calibration of standard candles, such as RR Lyrae stars, Cepheid variables and giants, used in establishing the extragalactic distance scale. Measurements of deviations from a Keplerian orbit offer the exciting possibility of exploring the cluster of stellar remnants surrounding the central black hole, suggested by Morris (1993), Miralda-Escudé & Gould(2000), and Freitag *et al.* (2006). Estimates for the mass of the remnant cluster range from $10^4 - 10^5 M_\odot$. Its absence would be interesting in view of the hypothesis that the inspiral of intermediate-mass black holes by dynamical friction could deplete any centrally concentrated cluster of remnants. Likewise, measurements of post-newtonian effects would also provide a test general relativity, and, ultimately, could probe the spin of the central black hole.

Tremendous observational progress has been made over the last decade towards obtaining accurate estimates of the orbital parameters for the fast moving stars at the Galactic center. Patience alone permitted new proper motion measurements that yielded the first accelerations (Ghez *et al.* 2000; Eckart *et al.* 2002), which suggested that the orbital period of S0-2 could be as short as 15 years. The passage of more time then led to full astrometric orbital solutions (Schödel *et al.* 2002, 2003; Ghez *et al.* 2003, 2005a), which increased the implied dark mass densities by a factor of 10^4 compared to earlier velocity dispersion work and thereby solidified the case for a supermassive black hole. The advent of adaptive optics introduced radial velocity measurements of these stars (Ghez *et al.* 2003, Eisenhauer *et al.* 2003, 2005), which permitted the first estimates of the distance to the Galactic center from stellar orbits.

In this paper, we present new orbital models for S0-2, which provide the first estimates based on data collected with the W. M. Keck telescopes of the distance to the Galactic center. New astrometric and radial velocity measurements have been collected between 2004 and 2007, increasing the quantity of kinematic data available, and the majority of the new data was obtained with the laser guide star adaptive optics system at Keck, improving the quality of the measurements (Ghez *et al.* 2005b; Hornstein *et al.* 2007); Additionally, new data analysis has improved our ability to extract radial velocity estimates from past spectroscopic measurements, allowing us to extend the radial velocity curve back in time by two years. A full presentation of these results can be found in Ghez *et al.* (2008).

2. Results & Discussion

Orbit modeling of astrometric and radial velocity measurements of short period stars provides a direct estimate of the Milky Way's central black hole mass and distance. While it is possible to get very *precise* estimates of these quantities from existing data sets, this study shows that there are systematic uncertainties that must be accounted for to obtain *accuracy* in these estimates. Since a dominant source of systematic error in the data set

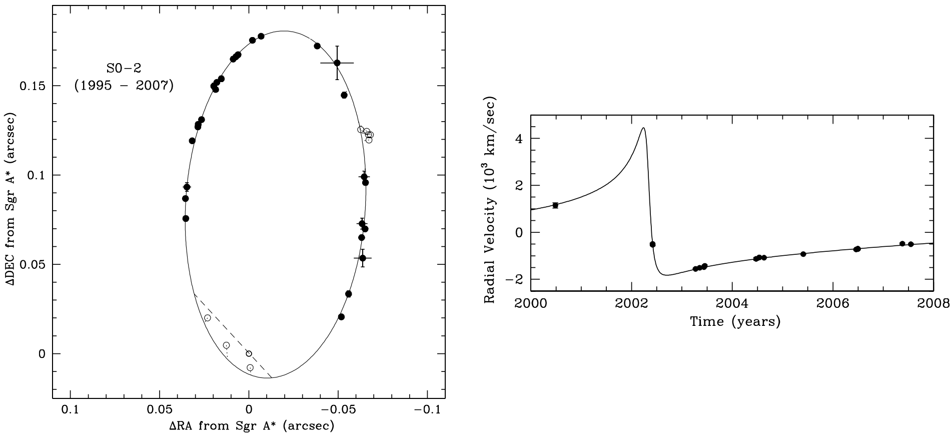

Figure 1. The best fit Keplerian orbital model with the astrometric and radial velocity data. The filled points were included in the formal fit, while the unfilled points are measurements that are excluded due to source confusion. Uncertainties are plotted on all points, except the unfilled/excluded points (here the uncertainties are comparable to the size of the points) for clarity. The data are well reproduced by a ten parameter model, which includes the black hole's mass, distance, and location in the plane of the sky as free parameters, and results in a reduced $\chi^2 \sim 1$ with the original estimates of the uncertainties. Dotted lines connect the measurements with their predicted location from the model, the dashed line shows the line of nodes, and the location of the black hole is marked by a circle, whose radius is approximately the black hole's positional uncertainty.

appears to be source confusion, we use only data from the brightest short orbital period star, S0-2, and only those measurements that are not confused with other known sources (see Figure 1). This results in a central black hole mass of $4.8 \pm 0.3 \times 10^6 M_\odot$ and distance of 8.3 ± 0.3 kpc (see Figure 2).

Our dynamical mass is larger than the $\sim 2-3 \times 10^6 M_\odot$ inferred from using projected mass estimators to derive the mass from measured velocity dispersions, even after accounting for the differences in distances (e.g, Eckart & Genzel 1997; Genzel et al 1997; Ghez *et al.* 1998; Genzel *et al.* 2000; see also Chakrabarty & Saha 2001). This discrepancy most likely arises from the assumptions intrinsic to the use of projected mass estimators. In particular, the projected mass estimators are based on the assumption that the entire stellar cluster is measured, which is not the case for the early proper motion studies as their fields of view were quite small (r $\sim$ 0.1 pc). Such pencil beam measurements can lead to significant biases (see discussions in Haller *et al.* 1996; Figer *et al.* 2003) An additional bias can arise if there is a central depression in the stellar distribution, such as that suggested by Figer *et al.* (2003). These biases can introduce factors of 2 uncertainties in the values of the enclosed mass obtained from projected mass estimates and thereby account for the difference between the indirect mass estimate from the velocity dispersions and the direct mass estimate from the orbital model fit to S0-2's kinematic data.

A higher mass for the central black hole brings our Galaxy into better agreement with the $M_{bh} - \sigma$ relation observed for nearby galaxies (e.g., Ferrarese & Merrit 2000; Gebhardt *et al.* 2000; Tremaine *et al.* 2002). For a bulge velocity dispersion that corresponds to that of the Milky Way ($\sim$100 km s^{-1}), the $M_{bh} - \sigma$ relationship from Tremaine *et al.* (2002) predicts a black hole mass of 9.4×10^6 $M_\odot$, which is a factor of 5 larger than

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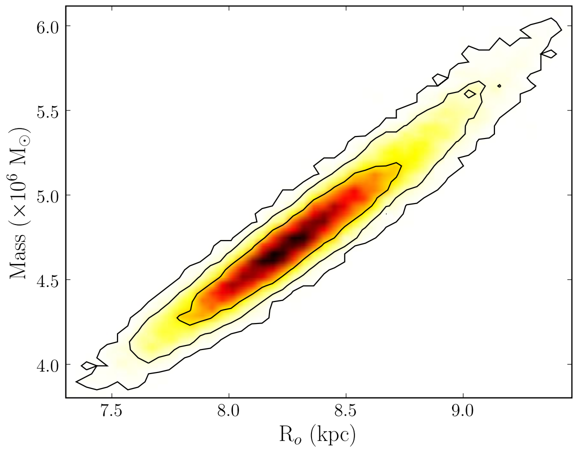

Figure 2. The probability distribution for central black hole's mass and distance from model fits to the orbit of S0-2. The best fit models imply a mass of $4.8 \pm 0.3 \times 10^6 M_\odot$ and distance of 8.3 ± 0.3 kpc. These quantities are not independent and the exact scaling depends on the relative impact of the astrometric and radial data on the model fits. Currently, the inferred mass scales with the inferred distance as $M \propto {R_0}^{1.8}$.

the value of the Milky Way's black hole mass used by these authors (1.8×10^6 $M_\odot$ from Chakrabarty & Saha 2001). The black hole mass presented here is a factor of of 2.7 larger than that assumed by Tremaine *et al.* (2002), bringing the Milky Way more in line with this relationship. With one of the most accurate and lowest central black hole masses, the Milky Way is, in principle, an important anchor for the $M_{bh} - \sigma$ relationship. However, the velocity dispersion of the Milky Way is much more uncertain than that of other nearby galaxies. Therefore our revised mass has only modest impact on the coefficients of the $M_{bh} - \sigma$ relation. More importantly, our revised mass estimate shows that factors of two changes in the black hole mass obtained from projected mass estimators are easily obtained and that much of the scatter in the $M_{bh} - \sigma$ relationship may easily arise from inaccuracies in the modeling of the black hole masses.

Revision of the central black hole's mass and distance can also, in principle, impact our understanding of the structure and timescales within our galaxy both on small and large scales. On the large scale, if we assume that the black hole is located at the center of our Galaxy, then its distance provides a measure of R_0. Its value from this study is consistent with the IAU recommended value of 8.5 kpc as well as the value of 8.0 ± 0.5 kpc suggested by Reid (1993), based on a "weighted average"† of all prior indirect measurements of R_0. Combining the value for R_0 from this study with the measured proper motion of Sgr A* along the direction of Galactic longitude (Reid & Brunthaler 2004; $\mu_{SgrA*,long}$ = -6.379 ± 0.026 mas yr^{-1}) and the Sun's deviation from a circular orbit (Cox 2000; 12 km s^{-1}) in the direction of Galactic rotation, we obtain an estimate of the local rotation speed, θ_0, of 255 ± 13 km s^{-1}, which is consistent with other recent measurements; these include a value of 222 ± 20 km s^{-1} from the review of Kerr & Lynden-Bell 1986 and 270 km s^{-1} derived by Méndez *et al.* 1999 from the absolute proper motions of ∼30,000 stars in the Southern Proper-Motion survey. As two of the fundamental Galactic constants, R_0 and θ_0 are critical parameters for axisymmetric models of the Milky Way. Under the assumption that the stellar and gas kinematics within our galaxy are well measured, the

† consensus value with consensus errors

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values of R_0 and θ_0 determine the mass and shape of the Milky Way (Olling & Merrifield 2000; Olling & Merrifield 2001). Of particular interest is the value of the short-to-long axis ratio of the dark matter halo, q, as it offers a valuable opportunity to distinguish between different cosmological models. As Olling & Merrifield (2001) demonstrate, the uncertainty in q for the Milky Way is dominated by the large uncertainties in R_0 and θ_0. Based on this analysis, which is predicated on axisymmetric models of the Milky Way, a value of 8.3 kpc for R_0 and 255 km $s^{-1}$for θ_0 suggests that a highly flattened dark matter halo can be ruled out; this in turn disfavors two dark matter candidates (1) decaying massive neutrinos and (2) a disk of cold molecular hydrogen (Olling & Merrifield 2001).

Closer to the black hole, knowing its mass and distance from the Sun improves our ability to study the kinematics of stars within its sphere of influence. With the black hole's parameters in hand, much less kinematic information is needed to determine the orbital parameters for stars whose motion is dominated by the gravitational influence of the central black hole. This approach was used to estimate the possible range of orbital periods for the fast moving stars within $0.''5$ of the central black hole, leading to the realization that these stars could have orbital periods as short as 15 years (Ghez *et al.* 2000; Eckart *et al.* 2002), which has indeed turned out to be the case (e.g., Schödel *et al.* 2002, 2003; Ghez *et al.* 2003, 2005; Eisenhauer *et al.* 2005). Further improvements in the constraints on the central black hole's properties and their degeneracies, as presented here, along with improved astrometry, has allowed us to derive orbital information for individual stars at much larger galacto-centric distances. With these measurements, in Lu *et al.* (2006), we test for the existence and properties of the young stellar disk(s), proposed by Levin & Beloborodov (2003) and Genzel *et al.* (2003b) from a statistical analysis of velocities alone. The direct use of individual stellar orbits out beyond a radius of $1''$ reveals the existence of only one, relatively thin, disk of young stars (Lu *et al.* in prep).

On an even smaller scale, the mass and distance of the black hole set the magnitude and time-scale for various relativistic effects. Given estimated Keplerian orbital elements for stars at the Galactic center, we expect to able to measure their stellar orbits with sufficient precision in upcoming years to detect the Roemer time delay, the special relativistic transverse Doppler shift, the general relativistic gravitational red-shift, and the prograde motion of periapse (e.g., Weinberg *et al.* 2005; Zucker & Alexander 2007). The most likely star to be measured first is S0-2, as it has the shortest orbital period (P=15 yr), is quite eccentric (e=0.8830) and, as one of the brighter stars (K_{S0-2} = 14.0 mag), has more precise astrometric and spectroscopic measurements. The radial velocity signatures of the first three effects are expected to be comparable to each other and will impart a ~200 km/s deviation at closest approach (Zucker & Alexander 2007), when the star is predicted to have a line of sight velocity of -2600 km/s based on our updated Keplerian model. This effect is large compared to the radial velocity precision ($\sim$ 20 km/sec). Likewise, the expected apoapse center shift for S0-2, $\Delta s = \frac{6\pi G M_{bh}}{R_0(1-e)c^2} = 0.9$ mas (see e.g., Weinberg 1972; Weinberg *et al.* 2005), is an order of magnitude larger than our current measurement precision ($\sigma_{pos} \sim 0.1$ mas). While stellar confusion in our present day adaptive optics measurements limits the accuracy of S0-2's positional estimates to only $\sim$ 0.5 mas, improved adaptive optics systems on existing telescope and larger telescopes (see Weinberg *et al.* 2005) will improve the sensitivity to the predicted apocenter shift. To put this measurement into context with existing tests of general relativity, it is useful to note that one of the strongest constraints on general relativity to date comes from the Hulse-Taylor binary pulsar, PSR 1913+16, which has a relativistic parameter at periapse, $\Gamma = r_{sch}/r_{periapse}$, of only 5×10^{-6}, which is 3 order magnitude smaller than that of S0-2

(Taylor & Weisberg 1989; Zucker & Alexander 2007). The stars at the galactic center are therefore probing an unexplored regime of gravity, which, in its strong regime, is the least tested of the four fundamental forces of nature, and, with the larger black hole mass implied by the measurements presented here, the relativistic effects should be larger than previously anticipated.

Precession from general relativistic effects also influences the timescale for resonant relaxation processes close to the black hole (see, e.g, Rauch & Tremaine 1996; Hopman & Alexander 2006). When precession from general relativity dominates over that from the extended mass distribution, the resonant relaxation timescale is proportional to $M_{bh}^2 \times (J_{LSO}/J)^2 \times P$, where J and J_{LSO} are the orbital angular momenta for the orbit of interest and at the last stable orbit around the black hole, respectively, and P is the orbital period. For a given semi-major axis and accounting for the linear mass dependence of $(J_{LSO}/J)^2$, this results in a $M_{bh}^5/2$ dependency. Thus the higher black hole mass inferred from this study increases the timescale over which the black hole's loss cone would be emptied in the regime where general relativity dominates. For the regime where extended mass distribution dominates, the resonant relaxation timescale scales only as $M_{bh}^1/2$. A higher black hole mass also implies a longer period for the last stable orbit. If the central black hole is non-spinning, the innermost stable orbit has a period of 38.5 min. Periodicities on shorter timescales, such as the putative QPO at ~ 20 min (Genzel. et al. 2003a; Eckart *et al.* 2006; Bélanger *et al.* 2006) have been interpreted as arising from the inner most stable orbit of a spinning black hole. At the present mass, the spin would have to be 0.6 of its maximal rate to be consistent with the possible periodicity. However, it is important to caution that other mechanisms can give rise to such short periodicities, such as a standing wave pattern recently suggested by Tagger & Melia (2006). A further complication is that the temporal power spectrum is also statistically consistent with that observed from red-noise caused by disk instabilities (Do *et al.*, in prep).

3. Conclusions

The short orbital period star S0-2 has been intensively studied astrometrically (1995-2007) and spectroscopically (2000- 2007) with the W. M. Keck 10 meter telescopes. Fits of a Keplerian orbit model to these data sets, after removing data adversely affected by source confusion, result in estimates of the black hole's mass and distance of $4.8 \pm 0.3 \times 10^6 M_\odot$ and 8.3 ± 0.3 kpc, respectively. While the current analysis is dominated by 11 years of astrometric measurements that have ~ 1.2 mas uncertainties, the LGSAO data over the last 3 years have positional uncertainties that are an order of magnitude smaller. With higher strehl ratios and more sensitivity, LGSAO measurements are also less effected by source confusion; this is especially important for the closest approach measurements, which have to contend with source confusion from the variable source SgrA*-IR. Following S0-2 for another 10 years should result in the first measurement of the Sun's peculiar motion in the direction of the Galactic center from the orbit of S0-2 with a precision of a few km s^{-1} and 1% measurement of R_0. At this precision, the measurement of R_0 is of interest because it may be able constrain the cosmic distance ladder.

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