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# Towards Complete Stellar Orbits around the Galaxy's Central Black Hole: The First Acceleration Measurements

Cont. Note

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**Abstract.** Four years ago, we initiated a proper motion study of the Galaxy's central stellar cluster using diffraction-limited K[2.2μm]-band images obtained with the W.M. Keck I 10-m telscope. With relative positional accuracies of ~3 milliarcsec, we have been able to measure stars moving with velocities up to 1400 km/s and, for the first time ever, accelerations of 1-3 mas/yr$^2$ (0.1-0.3 cm/s$^2$) at projected distances from the apparent radio counterpart of the black hole, Sgr A*, of 0.004 pc (0.1 arcsec). These measurements have not only provided us with direct dynamical evidence for a $2.6 \times 10^6$ $M_\odot$ central black hole, but have also permitted us to begin to constrain the orbits of these stars, which appear to be bound to the central mass. Continued study of these orbits (which possibly have periods as short as 10 years) will allow us to infer the radial distribution of dark matter within a few hundredths of a parsec around the black hole.

## 1 Introduction

In 1995, we began a 2μm diffraction-limited proper-motion program with the Keck 10-m telescope of the inner $5'' \times 5''$ of stars in the Galaxy's central stellar cluster in order to assess whether or not our Galaxy contains a supermassive central black hole. The first stage of this experiment was to obtain two-dimensional velocity measurements, from which a statistical estimate of the mass distribution could be determined. Analysis of the data obtained between 1995-1997 yielded two-dimensional velocity measurements for 90 stars, with velocities as high as 1400 km/sec, and clearly demonstrated the existence of a $2.6 \pm 0.2 \times 10^6 M_\odot$ black hole at the center of our Galaxy (Ghez et al. 1998). Since 1997 an additional 6 maps have been obtained, extending the time baseline to 4 years. With the new data, the velocity uncertainties are reduced by a factor of 3 and a similar mass estimate is derived. This is consistent with earlier work (Eckart et al. 1997; Genzel et al. 1997), although in our experiment the source confusion is reduced by a factor of 9, the number of stars with proper motion measurement in the central 25 arcsec$^2$ is doubled, and the accuracy of the velocity measurements in the central 1 arcsec$^2$ is improved by a factor of 15 over a comparable time period. In addition to simply increasing the time baseline for velocity measurements, we have advanced this experiment in two significant ways which are reported here: (1) The first Keck adaptive optics images of the galactic center have been

obtained, allowing us to obtain a more complete census of stars in this region, and (2) the first measurements of stellar accelerations in this field have now been achieved.

## 2 From Speckle Imaging to Adaptive Optics

First light with the Keck II Adaptive Optics (AO) system, which contains a 349-actuator deformable mirror and a 256x256 NICMOS array science camera, was obtained on 1999 February 4. We observed the Galactic Center on 1999 May 26 as part of the early science program, in order to test the system's ability to image a crowded field while correcting on a relatively faint (R = 13.7 mag) guide star located 30 arcsec off-axis (Wizinowich et al. 2000). Figure 1 shows a comparison of the new AO image with a typical speckle image during the same month. Although the cores of both the speckle and AO point spread functions are approximately diffraction-limited, the halos are greatly reduced in the AO image, leading to a factor of three higher Strehl ratio. With AO imaging, we can now identify stars much closer to the brighter stars, which increases the sample by a factor of two when the limiting magnitude of stars included is not changed ($K \leq 16$ mag). It should also be noted that the AO image represents only 75 sec of integration on source, whereas the speckle image has a total integration time of 1600 sec. With longer integration times, AO should allow us to (1) probe yet a larger sample of fainter stars, (2) place stringent limits on Sgr A*, and (3) explore the possibility of a gravitational lensing experiment (Alexander & Sternberg 1999). For the time being, the AO map has permitted us to increase the number of stars in the proper motion study.

## 3 From Velocities to Accelerations

With relative positional accuracies of ~3 milliarcsec, we can now fit the motions of stars with a second order polynomial as opposed to a simple linear fit, which was done in our earlier work. Figure 2 shows the two stars with the clearest measurements of an acceleration term. These two stars are also distinguished as the two fastest moving stars and the two closest to the nominal position of Sgr A*. The magnitudes of the two-dimensional acceleration vectors are 1.2 & 2.7 mas/yr$^2$, respectively, for S0-1 & S0-2, or equivalently 0.15 & 0.33 cm/sec$^2$, consistent with the order of magnitude expected for objects in orbit around a central mass concentration of $2.6 \times 10^6 M_\odot$, allowing for projection effects. For comparison, one anticipates, in the case of a face-on circular orbit of radius 0.″1 (the average projected radius for the two stars), an acceleration of 2.4 cm/sec$^2$. Futhermore, the direction of the projected acceleration vectors, which should intersect at the location of the dynamical center, is consistent with a large mass concentration at the position of Sgr A*.

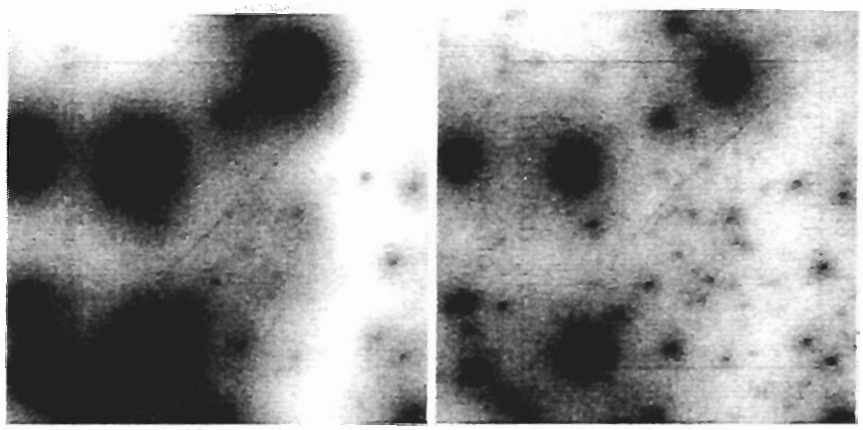

**Fig. 1.** A $\sim 3'' \times 3''$ region showing the Sgr A* cluster (the faint stars located just to the right of the center of the field of view). Both images were taken in 1999 May at 2.2μm (K-band), however the image on the left was produced by shift-and-adding Keck I speckle data and the image on the right was obtained with the new Keck II adaptive optics system. The adaptive optics image represents a large improvement (see text for details).

It is now possible to begin to explore individual orbits. Currently we have demonstrated that these two stars' motions can indeed be fit by bound orbits around a central mass of $2.6 \times 10^6 M_\odot$ under the assumption that the true focus is coincident with the location of Sgr A* (see Figure 3). High quality orbital fits are found for the two stars, with periods ranging from 15 - 550 and 35 - 1200 years for S0-2 and S0-1, respectively. Although the fits are not yet unique, they have dramatically constrained the possible orbits; less than 1% of the explored parameter space provides a good fit to the data.

## 4 The Future

With the new AO system, we hope to soon add measurements of the radial velocities, giving us the three-dimensional velocity vectors. With systematic proper motion and radial motion measurements, we will be able to derive the true orbital parameters for the individual stars. The ultimate goal is to be able to release the two critical parameters that are currently being held fixed: the total mass and the true focus. These measurements are particularly important as they would allow us to address the following questions:
[1] Is the $2.6 \times 10^6 M_\odot$ inferred for the central dark mass concentrated in a single black hole, or is a measurable fraction of it present in the form of a compact cloud of stellar remnants, dark matter particles (Salati & Silk 1989, Tsiklari & Viollier 1998; Gondolo & Silk 1999), or other forms of dark matter? The current statistical estimates on the distribution of dark matter at the galactic center only confine it to radii less than ~0.01 pc (0.25 arcsec).

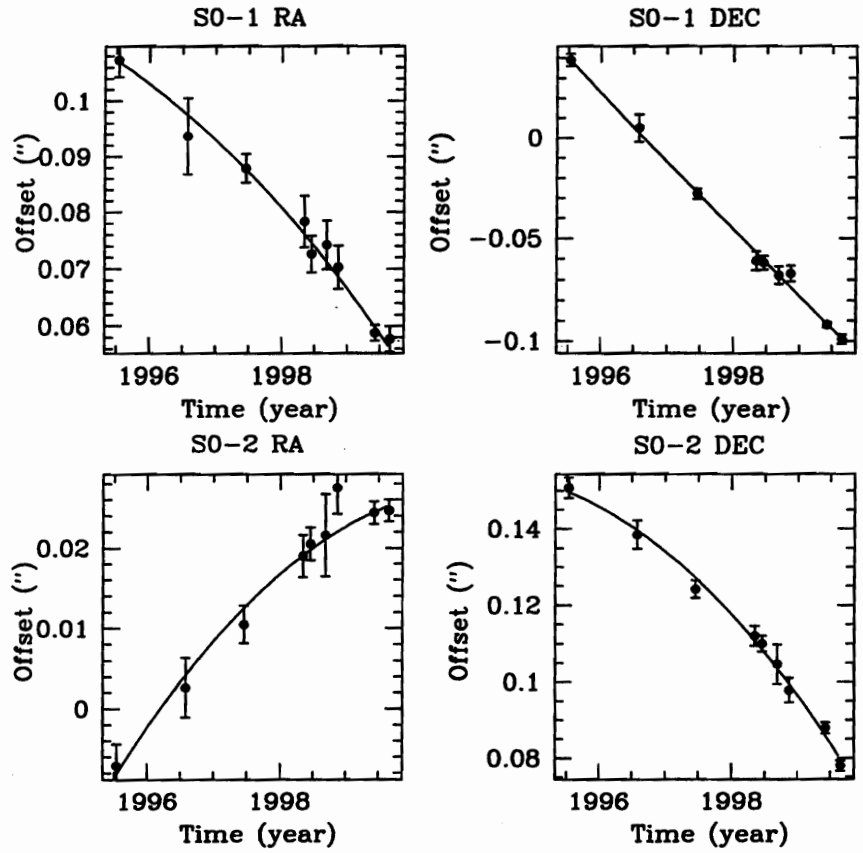


**Fig. 2.** East-West and North-South positional offsets from the nominal location of Sgr A* are plotted as a function of time for the two stars, S0-1 & S0-2, that have the most significant acceleration measurements. It should be noted that the offset range shown is scaled to the points in each plot and therefore varies from $\sim 0.''04$ to $\sim 0.''15$. The solid line in each plot shows the model used to assess the acceleration term: a second order polynomial with a time zero-point fixed to 1995. Both the magnitude and direction of these accelerations are consistent with at $2.6 \times 10^6 M_\odot$ black hole located at the position of Sgr A*.

However, we now can begin to use the orbits of stars such as S0-1 and S0-2, which are located only about 0."1 (0.004 pc) away from Sgr A*, to either push the limits on the volume of the central dark matter concentration down by an order of magnitude, or to resolve any mass distribution that might be present. Every individual star with a measurable orbit becomes a separate and independent probe of the interior mass, so by comparing stellar orbits displaying a range of semi-major axes, but modest eccentricities, we will be

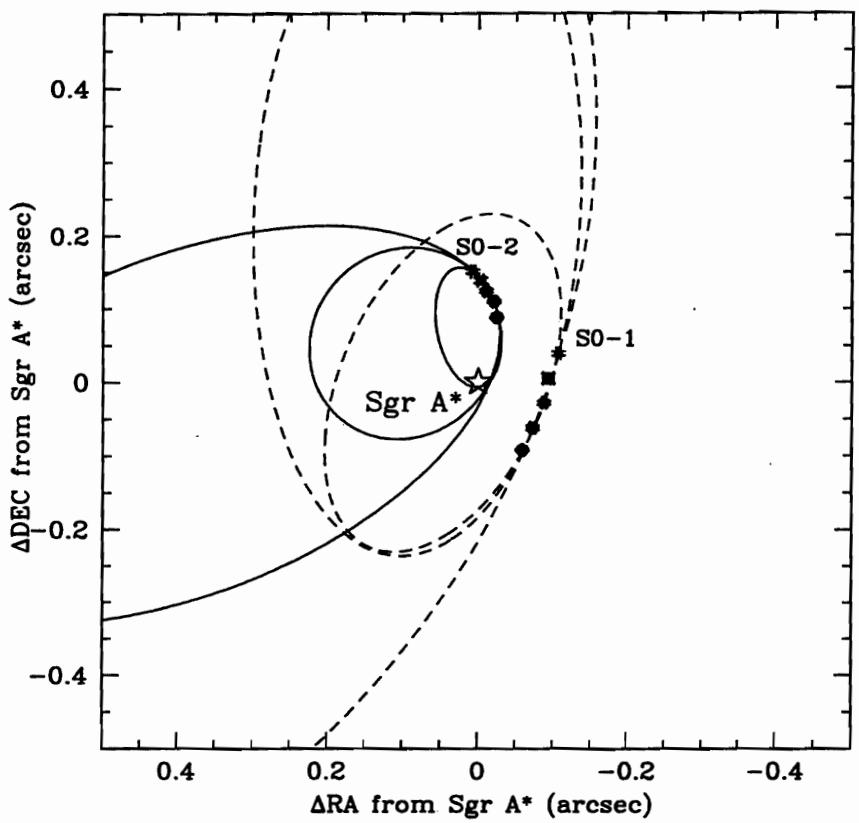


**Fig. 3.** A 1″ × 1″ region, centered on the nominal position of Sgr A*, showing the motion of S0-1 & S0-2 and possible orbital solutions. Only the measurements obtained in ~June of each of the 5 years are shown and both stars appear to be moving clockwise about Sgr A*. In the orbital analysis, two constraints are applied, a central mass of $2.6 \times 10^6 M_\odot$ and a true focus located at the position of Sgr A*. Displayed are orbital solutions ith periods of 17, 80, 505 years for S0-2 and 63, 200, 966 years for S0-1.

able to infer the presence of an entourage of dark matter around the black hole having a total mass as small as 10% of the mass of the black hole. [1]

[1] we note that orbital precession caused by an extended mass distribution can in principle have a contribution from General Relativistic effects for stars that pass within $\sim 10 R_{sh}$, should they survive the tidal forces. However, unraveling the General Relativistic effects would take a long time and none of the stars currently being tracked are predicted to get so close to Sgr A*.

[2] Is Sgr A* the central black hole? The orbits will pinpoint the dynamical center with a factor of 20 better accuracy than is possible with velocity information alone. With velocities only, the dynamical center can be located to within ± 100 mas ($1\sigma$), which shows that the dynamically-determined location of the dark matter concentration is statistically consistent with the position of the unusual radio source Sgr A*. However, this is inadequate to definitively associate Sgr A* with the black hole, given the complexity of the region.

[3] Are there deviations from Newtonian Gravitation at size scales on which it has not heretofore been accurately tested? While few will doubt that Newtonian Gravitation is accurate at scales of $10^{16} - 10^{17}$ cm, or thousands of AU, the nearly elliptical orbits that we are now measuring will provide the first real test on such size scales. The periods of normal binaries with such separations are far too long ($\sim 10^5$ yr) for such orbits to be accurately surveyed, but the time scale contraction wrought by a few million solar mass black hole makes such orbits measurable on a feasible time scale. We note that this question is closely coupled with question 1; any deviation from purely Keplerian orbits will be extremely interesting in one of the two stated respects, and multiple orbit determinations covering a range of size scales will sort out the dominant physics.

[4] Are the orbits isotropically distributed, or are the luminous stars inhabiting the central cusp characterized by a dominant radial or tangential velocity component? If the orbits are distributed anisotropically, is that a result of long-term dynamical processes or is it a dynamical remnant of the star formation process? With the orbits of a sizeable sample of stars, it is possible to constrain their dynamical evolution.

[5] What is the distance to the Galactic Center? These measurements will provide an independent measurement with an accuracy of a few percent (Salim & Gould 1999).

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