Milky Way Galactic Center Supermassive Black Hole Research Overview & its Stellar Orbit Analysis

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In this letter I present a brief history regarding the research of the Super Massive Black Hole (SMBH) at the Galactic Center (GC) of the Milky Way, following state of the art modern technology techniques to do so. I discuss the advantages of modern technologies and the problems it has solved (problems such as the earth's constant moving atmosphere interference which affects telescopes' measurements accuracy), which as a result, rapidly progressed our understanding of galaxies formations, and of course, one of the most fascinating celestial object in the universe – Black Holes. By virtue of the fact that black holes' mass density is so large its gravity is so powerful so that it does not emit any kind of particles nor any kind of electromagnetic radiation, a different research approach should be considered, such as – observing and analyzing its surrounding environment (nearby star clusters and gases), and by so – fitting variety of physical parameters of the directly-unmeasurable object: velocity, volume, rotating speed, and regarding the black hole in the center of our galaxy – the distance from our solar system and most important – its mass, which today is believed to be $3.67\ (\pm 0.19) * 10^{6}\ \mathrm{M}_{\odot}$.

Introduction – A black hole is an object in space that cannot send information outside of it, not in a matter of mass, nor electromagnetic radiation. Its boundary extent is called the *event horizon*[1], and only matter/energy farther than this boundary is detectable/measureable. In 1795 Laplace concluded using Newtonian gravity and Newton's corpuscular theory of light that light could not escape an extreme mass density object – that was the first glimpse for the idea of a black hole. In 1915, only a month after Einstein's publication of his work on general relativity, Karl Schwarzschild derived the relativistic solution to the gravitational field surrounding a spherical-shaped mass; this analytical solution was confirmed by Einstein himself [1]. Putting theory into practice, the most astonishing physical instrument used in astronomical research is the telescope. One of the first uses of optical interferometry was the construction of a Michelson stellar interferometer on the Mount Wilson Observatory's reflector telescope in order to measure the diameters of stars; the red giant star Betelgeuse was the first to have its diameter measured this way in 1920.

Full of Emptiness - The universe is mostly empty so electromagnetic radiation from far away galaxies travel across it with no significant decay. However, detecting a specific object inside a galaxy could be real challenge due to vast star dust and other interfering objects, and especially far objects from earth, like the surrounding of the black hole in the galactic center.

Radio interferometry – The radio telescopes which detects electromagnetic radiation plays an important role in astronomy. In the 1940s they were used to capture the first high resolution images. Until around 1970 the radio wavelengths were dominant in astronomical researches. Since then, in order to get even more high resolution images an array of telescopes has been built (e.g. VLA and ALMA). These physical instruments opened a new era for astronomical researches – specifically on black holes, which I will be focusing on.

Please stop moving! – One of the most hair ripping issues in astronomical observation is the constant moving earth's atmosphere and its turbulences which distort the light coming from distant space – meaning unfocused images. The field of correcting this problem is called Adaptive Optics (AO), which is basically deforming the telescope's mirror in order to compensate for the distortion of light it detects. This method have been used since the early 1990s [2]. However, the downfall of this technique is that the corrections can only take place for a fifth-magnitude stars for the optical spectrum observations and twelfth-magnitude for near-IR wavelengths (a thousand times fainter). A solution for this has been developed using lasers, and is called Laser Guide Star (LGS). Using a sodium wavelength laser, directed to the sky, the atmosphere turbulences movement could be detected and analyze in such a way that the light coming from space is "reversed engineered" according to the distortion of the laser. This technique results in a dramatically more sharpened/focused images. It was installed on the Keck II telescope in 2001. There are of course dozens of space telescopes today – which do not meet any kind of

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[1] Scientifically named *Schwarzschild radius* or *The Static Limit*, because object that enters this extent will seem to stop moving due to the strong gravitation of the black hole.

atmospherical issues, but I will be focusing on the researches that were done using ground telescopes.

Cut to the chase - Since the invention of the optical and radio telescopes, and its developing technology, like the LGS I had mentioned, there is growing observational evidences of the existence of a black hole at the centers of many nearby galaxies. A definite proof for the existence of black hole as described by general relativity requires the determination of the gravitational potential up to the extent of the event horizon I mentioned before. This can be achieved by analyzing stellar gas or stars that are in close orbit to the black hole. However, using this method, it is not yet possible determining the event horizon scale, but only the black hole's presence due to the face that no other known celestial object has such extremely large mass density [3]. In the following paragraphs I will present the results of telescope observations which confirm the existence of the black hole in the center of the Milky Way galaxy. This is the time to mention that black hole is classified into 4 types detailed in Table I.

Black Hole Class	Mass	Size
Micro	$up\ to \sim M_{moon}$	up to ~0.1 mm
Stellar	$\sim 10\ M_{\odot}$	~30 km
Intermediate-mass	$\sim 10^3\ M_{\odot}$	$\sim 10^3\ km \approx R_{earth}$
Supermassive	$\sim 10^5 – 10^{10}\ M_{\odot}$	~0.001–400 AU

Table I - Black Hole classifications (1 AU = Earth-Sun Distance)

The black hole in the center of the Milky Way is classified as Supermassive black hole – and it will be shown as a results from analyzing observational data sets.

Observations – As early as 1980, radio observations revealed that gas was swirling around a dark, massive object at the center of the galaxy. That object, which glowed steadily at radio wavelengths, was designated Sagittarius A* for its location in the constellation Sagittarius. And by the early 90's, observations of the motions of stars and gas clouds suggested the dark object was more than two million times as massive as the Sun – meaning, a black hole.

Stellar Orbits Analysis – As I said in the beginning of this article, the supermassive black hole in the GC does not emit any kind of information - as light cannot escape it, thus we cannot measure it directly. The approach (or technique) used to work around this issue is by observing the SMBH's environment, that is, interstellar dust and stars orbiting it. I will discuss two methods to do so.

First Method: *Simple 1-Star Orbit Analysis*

Through the years 1992 and 2002 the European Southern Observatory (ESO) had taken HD IR images of the central few light years of our Milky Way for a detailed study of the stellar dynamics in the vicinity of the compact radio source Sagittarius A*. Using statistical analysis of these dynamics – it was deduced of an existing mass of about 2.6 to 3.3 million sun masses within an extent of ten light days of Sagittarius A*. In 2002 the orbiting star S0-2 had approached Sgr A* to within 10 – 20 mas, which provided a unique opportunity to determine the mass a factor of 10–20 times more closely than in previous measurements [4].

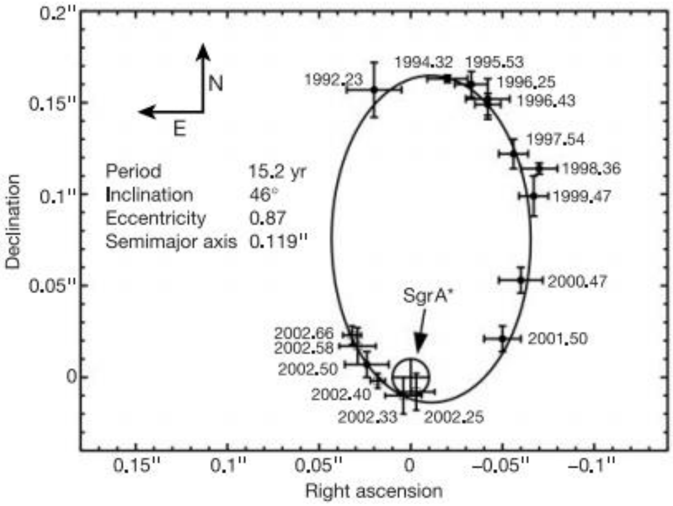

Figure 1 – S0-2 measurements fitted into keplerian orbit trajectory around Sagittarius A* (marked as ⊕, denoting $\pm 10\ mas$ uncertainties of the IR astrometry used).

The first measurements of orbital accelerations for S0-2 that were made were consistent with orbit bound to a central object of $\sim 3 * 10^6\ M_{\odot}$, but still allowed a wide range of possible orbital parameters ranged from 15 to 500 years [5]. Due to the close approach of S0-2 to Sgr A* it was possible to determine a unique orbit for S0-2 from astrometric proper motions and provide strong constraints on the mass distribution on distances less than one light day. Figure 1 displays the measured positions of S0-2 star relative to Sagittarius A*.

As I mentioned earlier, S0-2 approached very close to Sgr A*. It has reached a velocity of $5{,}000\ km/sec$, approximately 8 times greater than in 1994.4 when it reached the apocenter. The S0-2 data points trace about two-thirds of a closed orbit and fits by a bound keplerian orbit around a central point mass located at the position of Sgr A*. This fit resulted two important parameters: Sgr A* Mass and S0-2 orbit period (Table II).

Parameter	Value
Sgr A* Black Hole Mass	$3.7\ (\pm 1.0) * 10^6\ M_{\odot}$
S0-2 Period	$15.2 \pm 0.6\ years$

Table II – Parameters calculated using S0-2 keplerian orbit fit results

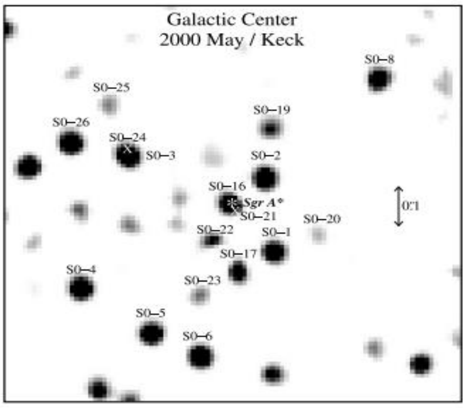

Figure 2 - Central 1''x1'' of the match filter for the 2000 May data set. 15 sources identified successfully. 2 were ignored (marked with a cross) due to a confusion with a brighter source nearby. An asterisk denotes the black hole's position.

For the nominal Sgr A* position, the uncertainties of the fitted parameters are generally less than ten percent. The additional uncertainty of astronomic errors is about ten percent as well. The semimajor axis ($\sim 5.5\ light\ days$) and orbital period of 15.2 years imply a mass of $3.7(\pm 1.5) * 10^6\ M_{\odot}$. The remarkable consequence of the orbital technique is that the mass can be determined from a single stellar orbit, in comparison to the statistical techniques that use several tens to hundreds of stellar velocities at 10 to 300 light days from Sgr A* (Fig. 3). In addition, the orbital technique requires fewer assumptions than the other estimates (for example, equilibrium and isotropy of orbits), and thus is less vulnerable to systematic effects.

Second Method*: Multi Stars Simultaneous Fitting*

Using Keck I telescope and its near infrared camera a series of short exposure images were taken between the year 2000 and 2003 at the Sgr A* area. These data sets were collected and analyzed: each frame, with a scale of $20.396 \pm 0.042\ mas/pixel$, and a corresponding field of view of $5''.22^2$, was sky-subtracted, flat-fielded, bad-pixel–corrected, corrected for distortion effects, and magnified by a factor of 2. The images have been merged and shifted together forming a shift-and-add maps which have point-spread functions (PSFs) [6].

Analyzing – In order to identify each star captured, a "match filter" is applied to the images by correlating it with the core of its PSF, out to a radius of 0".06 (see figure 2). In the first pass at source classification, correlation peaks larger than a defined boundary were flagged as stars. Once they are identified, a second lower boundary is used in order to track down these stars in images in which they were not identified with the first threshold value. This second step search is limited to within a specified radius of the expected star's position. Stars that passes the third boundary condition are included in the final proper-motion sample.

Photometric values are estimated using two techniques. First, simple aperture photometry which allows to track the sources in the data sets. Second, PSF fitting with StarFinder is implemented. While many stars are identified over the 5"x5" field of view, this specific study is limited to sources within a radius of 0".4 of the IR position of Sgr A^* - which is the best radio source candidate in the galactic center for the position of the supermassive black hole.

Significant curvature or linear acceleration in the surface of the sky is detected for 7 out of 17 sources shown in the appendix (Table III). Stars are considered to show significant deviations from linear proper motion, if they have $\Delta\chi^2_{tot}$, which is the difference between the total χ^2 from the best second order polynomial fit, greater than 15; An analyze has been made for these 7 stars.

Physical Modeling – The assumption is that gravitation potential exists to due to a single point mass, which allows all surrounded stars to contribute to the solution for the physical parameters: Mass, Location and Linear motion on the plane of the sky. In the analysis, the source's distance and its linear motion along the line of observation are not solved for; to get the Mass, the distance is assumed to be 8 kpc, while the line of observation is set to zero; this is reasonable because the resulting limits on the value of the black hole's Right Ascension and Declination motion ($\leq 76\ km/sec$) are comparable to the uncertainties on the radial speed measurements for S0-2 ($\sim 40\ km/sec$), which are the only radial velocity used in this model's analysis. In addition, there are six free parameters for each source/star: period, eccentricity, time of periapse passage, inclination, position angle of the nodal point and longitude of periapse [7].

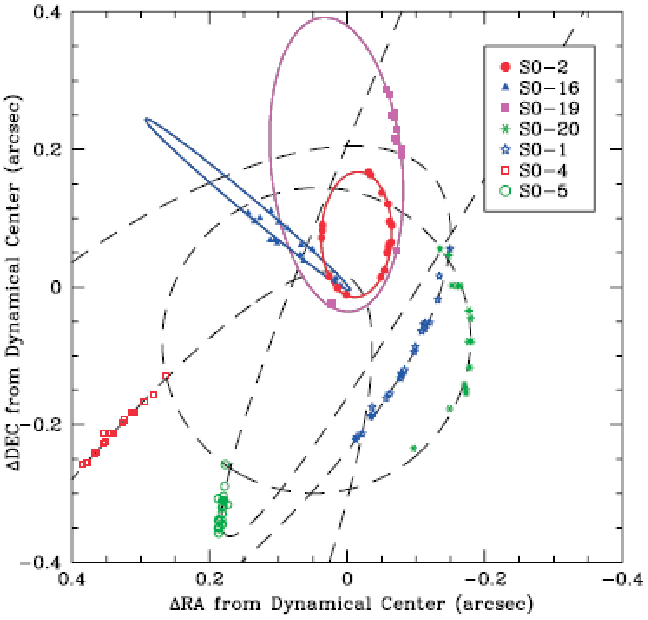

Figure 3 – Orbital stars trajectory fitted simultaneously. The data sets that were captured between 1995 and 2003 at the Keck telescopes have uncertainties that are comparable to or smaller than the size of the points, and are presented in the reference frame in which the central black hole is stationary.

Summing it up, the model used contains 5+6N parameters, where N is the number of stars participating the simultaneous fit process. This is better than simply averaging over the results of N independent orbiting stars, since each star in the simultaneous fit contributes to the determination of the parameters, which actually results in a better definition of each star's orbital parameters itself. The fitted trajectory shown in figure 3 resulted by minimizing χ^2 between the data sets used and the physical model described, while the reported uncertainties obtained from the covariance matrix. The data that has been used in this process consists of 254 measurements. The final results from the simultaneous fit sets the central dark mass at $3.67(\pm 0.19) * 10^6\ M_{\odot}$.

Summary & Conclusions – Astronomical observations fascinated human kind for ages. Today's modern technology and physical understanding lets us explore the universe origins and behavior like never before. Measuring techniques are improving exponentially, and these capabilities are taking part, for example, in discovering and identifying the monstrous 3.7-million-sun-masses celestial object in the center of our galaxy – the Supermassive Black Hole. As I've shown, the multi-star simultaneous fit was plotted better results than the 1-star fit, which is naturally logical due to the use of many sources/candidates at once in a synergy. In time, technology will advance, and the measuring/fitting techniques (and physical models) will improve – so we could understand even better the cosmos we live in.

[1] Stuart L. Shapiro & Saul A. Teukolsky, *Black Holes, White Dwarfs, and Neutron Stars: The Physics of Compact Objects*, p. 336.

[2] Peter L. Wizinowich et al., The W. M. Keck Observatory Laser Guide Star Adaptive Optics System: Overview, Astronomical Society of the Pacific, 118:297–309 (2006)

[3] R. Schodel et al., A star in a 15.2-year orbit around the supermassive black hole at the centre of the Milky Way. Nature 419, 694-696 (2002).

[4] Ghez, A., Morris, M., Becklin, E. E., Tanner, A. & Kremenek, T. The accelerations of stars orbiting the Milky Way's central black hole. Nature 407, 349–351 (2000).

[5] A. M. Ghen, B. L. Klein, M. Morris & E. E. Becklin, High proper-motion stars in the vicinity of Sagittarius A*: evidence for a supermassive black hole at the center of our galaxy, The Astrophysical Journal, 509:678-686, 1998 December 20

[6] A. M. Ghez et al, Stellar orbits around the galactic center black hole, The Astrophysical Journal, 620:744–757, 2005 February 20

APPENDIX

Star Name	Other Name	K (mag)	# of epochs		Closest measured position				σ_{pos} (arcsec)	$\Delta\chi^2$	Notes
			N_{det}	N_{fit}	Date (year)	R (arcsec)	ΔR.A. (arcsec)	Δ Decl (arcsec)			
S0-2	S2	14 ± 0.2	22	18	2002.309	0.012	0.000	-0.012	0.001	6132	
S0-16	S14	15.5 ±0.3	18	17	2000.305	0.006	0.005	-0.001	0.002	3570	New
S0-19	S12	15.5 ±0.2	13	12	1995.439	0.036	0.015	-0.033	0.002	936	New
S0-20	S13	15.7 ±0.2	15	15	2003.682	0.147	-0.136	0.057	0.004	286	New
S0-1	S1	14.6 ±0.1	22	22	1998.505	0.131	-0.117	-0.060	0.001	281	
S0-4	S8	14.4 ±0.1	22	21	1995.439	0.29	0.255	-0.137	0.001	53	
S0-5	S9	15.1 ±0.2	21	20	1995.439	0.316	0.169	-0.267	0.002	35	
S0-23	ID7	16.7 ±0.2	9	9	1996.485	0.157	-0.024	-0.155	0.005	14	New
S0-25	ID9	16.4 ±0.3	11	11	1998.771	0.364	0.262	0.253	0.006	10	New
S0-8	ID14	15.7 ±0.2	20	20	2003.303	0.39	-0.296	0.253	0.003	7	New
S0-17		15.8 ±0.2	16	6	2003.682	0.115	0.028	-0.112	0.004	6	New
S0-26	ID12	15.1 ±0.2	19	19	1997.367	0.385	0.366	0.12	0.002	6	New
S0-22		16.8 ±0.4	7	7	2001.572	0.093	0.031	-0.088	0.01	5	New
S0-24		15.7 ±0.2	5	5	1998.505	0.283	0.244	0.142	0.008	2	New
S0-6	S10	14.2 ±0.1	22	22	2003.682	0.378	0.058	-0.374	0.001	0	
S0-21		16.1 ±0.3	3		1999.56	0.009	-0.007	-0.006	0.006		New
S0-3	S4	14.4 ±0.2	22		1995.439	0.180	0.149	0.101	0.001		

Table III - Summary of Sources Identified within 0''.4 of the Central Dark Mass Observations