Characterization of the supermassive black hole of the MW through its orbiting stars

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INTRODUCTION

Understanding the formation and evolution of supermassive black holes is a big challenge for physicists and astrophysicists around the world. Not only these fascinating objects provide the ideal scenario for the study of high energy astrophysics but they could also teach us new physics that we are yet to discover. Given the relatively short distance at which the centre of the Milky Way is located with respect to us, we can focus some of our attention on the study of its supermassive black hole through various techniques. Being able to observe stellar orbits in the very centre of the galactic center (we refer to it as the orbital technique) that seem to revolve in the gravitational potential produced by a high concentration of mass is without a doubt a very conclusive evidence for the existence of the theoretically predicted supermassive black hole.

Before we could determine orbits around the central black hole of the MW, our best evidence to support the idea of its existence were measurements of stellar velocities and variable X-ray emission detections but these weren't enough to properly constrain the physical properties of this body. Now we can constrain the mass of the compact object via the study of the orbital parameters of its surrounding stars and also constrain more accurately its distance and location through the advances in adaptive optics techniques. Another great advantage of the orbital technique is that the mass can be determined in one single orbit in contrast with the statistical techniques that make use of hundreds of stellar velocities.

ORBITAL TECHNIQUE RESULTS

The first accurate and relevant measurements of a star orbiting the black hole were conducted by Schodel et al. 2002 [1] who reported ten years of astrometric imaging of a star that is located very close to the compact radio source Sgr A*. Their study shows a highly elliptical orbit with a period of ∼15.2 years and the best acquired orbital parameters are consistent with a central mass of $\sim 10^6 M_\odot$. One of the most important results of their work is that it allows them to exclude other scenarios that could in principle account for the motion of this star such as a cluster of dark astrophysical objects and degenerate fermions.

Later on, observations of the orbit of star S14 showed the mass of the BH to be $\sim 4.1\times10^6 M_\odot$ within a volume with radius no larger than $6.76.7\times10^9$ km. They also determined the distance from Earth to the Galactic Center (the rotational center of the Milky Way) as $8.0 \pm 0.6 \times 10^3$ pc.

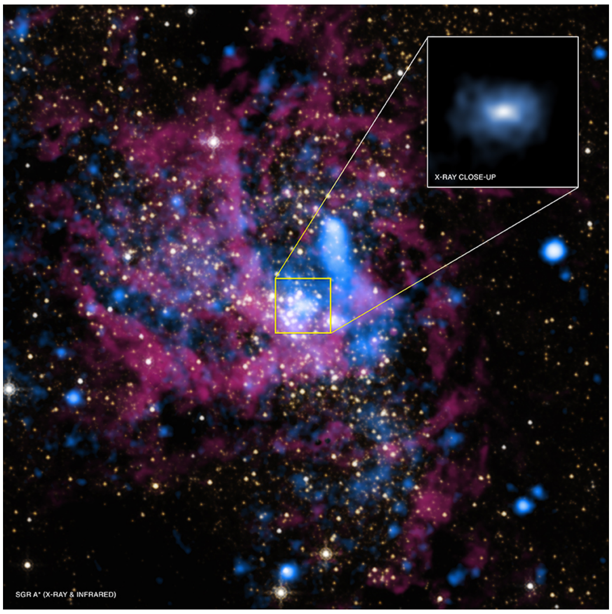

Figure 1: Location of Sgr A* in a X-ray and infrared constructed image. Credits to NASA

After observing stellar orbits around Sgr A* for 16 years, Gillessen et al. 2009 [4] estimated the BH mass of $4.31 \pm 0.38 \times 10^6 M_\odot$. They refined previous analysis with the use of the excellent astrometric accuracy of adaptive optics. Reinhard Genzel, who was the team leader of the research, quoted about the results "what is now considered to be the best empirical evidence that super-massive black holes do really exist. The stellar orbits in the Galactic Center show that the central mass concentration of four million solar masses must be a black hole, beyond any reasonable doubt."

A very puzzling question has to do with the existence of the stars in the innermost arcsecond (S-stars) around the supermassive BH. The issue about these stars surrounding the black hole comes in when analyzing their ages through spectroscopy; many of these stars are identified to be young main-sequence stars. These young stars are less than 10^6 years old and since the black hole is expected to have existed for at least 10^6 years there has to be a mechanism responsible for their existence different from our current model for star formation. This is the so-called "Paradox of Youth" as discussed by Ghez et al. 2003.

Currently, none of the solutions proposed so far for the puzzle of the young stars (such as Morris 1993; Genzel et al. 2003b; Ghez et al. 2003, 2005, etc.) are entirely satisfactory and they broadly fall into three categories. First, exotic modes of star formation near the massive black hole; second, rejuvenation of old stars in the local population; third, accelerated dynamic migration, or capture of stars from farther out.

The first category has to account for modifications in our star formation theories since according to standard scenarios of star formation and stellar dynamics the stars cannot be born in such an extreme environment (around a supermassive BH) because of the strong tidal shear, but are also too short-lived to have migrated there from farther out.

In the third category, stars develop somewhere else further away from the black hole, where the tidal forces aren't as strong. Then, once the cloud has collapsed and formed stars, these stars could migrate closer towards the black hole through some process. From the combination of their normal rotation and random orbital orientations, it's concluded that the S stars were most likely brought into the central light-month by strong individual scattering events. Current versions of this model propose that in order to migrate close enough to the black hole before the stars age too much, a star cluster resulting from the gas cloud would have to be very dense, so much that it would trigger a core collapse. In the core collapse, the stars in the cluster start a runaway process of falling towards the middle of the cluster, forming an intermediate-mass black hole (IMBH). The cluster, with the IMBH, would then migrate closer to the galactic center. Under this model, the young stars we see today would be those that avoided the fate of getting absorbed into the IMBH. Although this model is not confirmed, there is some evidence for the existence of an IMBH in the galactic center, which could support this model.

There are also more specific scenarios in the literature for delivering stars "individually" (i.e, with random orbital properties) to the center. Some of these models are: The dissolving sinking cluster (Portegies Zwart et al. 2003) bound by an intermediate-mass black hole (Hansen and Milosavljevic 2003). The massive binary exchange (Gould & Quillen 2003). Exchange capture with stellar black holes (Alexander & Livio 2004). It's fair to say that we are still far from understanding properly this paradox and there is a lot of work to do in understanding these proposed mechanisms.

In order to get a better understanding of the physical properties of the supermassive BH and its surrounding stars we need very accurate observational techniques. The advent of adaptive optics which is a technique that allows for a reduction of the effect of wavefront distortions (correcting the deformations of an incoming wavefront by deforming mirrors) meant a significant improvement in the measurements of the stellar orbits and high angular resolution spectroscopy. More specifically, the image quality, depth, and astrometric precision have all been greatly improved with the advent of LGSAO (laser guide-star adaptive optics).

Astronomers have been unable to observe Sgr A* in the optical spectrum because of the effect of 25 magnitudes of extinction by dust and gas between the source and Earth. Several teams of researchers have attempted to image Sgr A* in the radio spectrum using very-long-baseline interferometry (VLBI). It's important to note that the observations of S2 were made with near-infra red (NIR) interferometry (in the K-band, i.e. 2.2 μm) because of reduced interstellar extinction in this band. As we can see in figure [1], the central region of the MW is a very crowded volume so that we need to use the proper wavelength to go into its deep regions.

Parameter	**S1**	**S2**	**S8**	**S12**	**S13**	**S14**
a (")	0.412	0.1226	0.329	0.286	0.219	0.225
e	0.358	0.876	0.927	0.902	0.395	0.9389
P(yr)	94.1	15.24	67.2	54.4	36	38
t_0	2002.6	2002.315	1987.71	1995.628	2006.1	2000.156
$i(°)$	120.5	131.9	60.6	32.8	11	97.3
$\Omega(°)$	341.5	221.9	141.4	233.3	100	228.5
$\omega(°)$	129.8	62.6	159.2	311.8	250	344.7
PLTP^b(yr)	1.74e9	6.3e6	5.7e7	5.8e7	2.48e8	1.42e7

Table 1: Orbital parameters of S stars around Sgr A*. Data from Eisenhauer et al. 2005 [3]

ORBITAL MODELLING

Using the orbital parameters of table [1] we can plot the orbit of the reported stars around Sgr A*. We can use the algorithm suggested in [5]. First for the mean anomaly we take $M(t) = 360.0 - 360.0 \times \frac{t_0 - t}{P}$ and normalize it in the range $[0, 2\pi)$. Then we need to solve Kepler's equation for eccentric anomaly $E(t)$:

$$M(t) = E(t) - e\sin(E)$$

The latter can be solved using the numerical Newton-Raphson method where we find the zeros of the function:

$$f(E) = E(t) - e\sin(E(t)) - M(t)$$

Once we solve for the eccentric anomaly we can obtain the true anomaly as

$$\nu(t) = 2 \arctan 2(\sqrt{1+e} \sin E(t)/2, \\ \sqrt{1-e} \cos E(t)/2)$$

where arctan2 is the two-argument arctangent function also defined in [5]. With the eccentric anomaly we can calculate the distance to the black hole as:

$$r_c(t) = a(1 - e \cos E(t))$$

from where we can get the orbital positions:

$$o_x(t) = r_c(t) \cos \nu(t) \quad o_y(t) = r_c(t) \sin \nu(t)$$

Finally, to transform the orbital positions to the inertial frame in bodycentric rectangular coordinates we use the rotation matrices and the sequence:

$$\vec{r}(t) = R_z(-\Omega) R_x(-i) R_z(-\omega) \vec{o}(t)$$

so finally we get the Cartesian coordinates:

$$x(t) = o_x(t)(\cos \omega \cos \Omega - \sin w \cos i \sin \Omega) \\ -o_y(t)(\sin \omega \cos \Omega + \cos \omega \cos i \sin \Omega)$$

$$y(t) = o_x(t)(\cos \omega \sin \Omega + \sin \omega \cos i \cos \Omega) \\ +o_y(t)(\cos \omega \cos i \cos \Omega - \sin \omega \sin \Omega)$$

Following this model and using the reported orbital parameters we can reproduce the orbits of the stars as shown in figure [2].

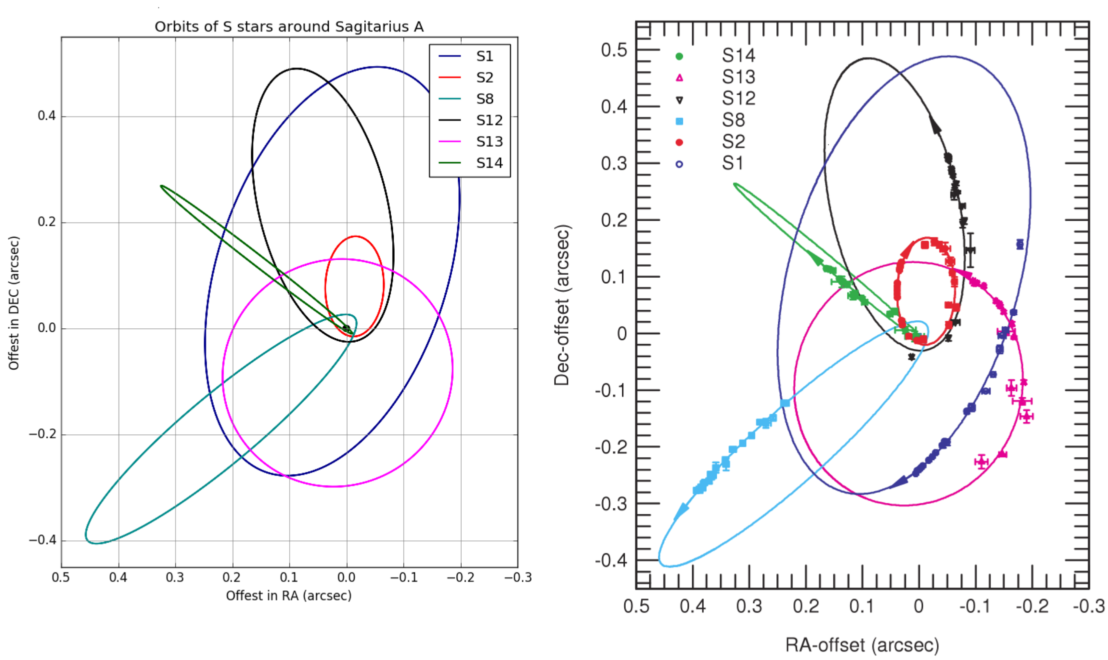

Figure 2: Projected orbits of the measured stars around the Milky Way's supermassive black hole. The coordinate system is chosen such that Sgr A* is at rest and in the origin. Left: The plots produced using data from table 1, from Eisenhauer et al. 2005 [3]. Right: Original plot from [4] and the observational data used to calculate the orbital parameters.

—->Read the python script that I wrote for plotting the orbits at:
`https://github.com/juancho9303/My_projects/blob/master/plot_orbits_SagA.py`<—-

CONCLUSIONS

The accurate determination of stellar orbital parameters of S-Stars around Sgr A* has shown us clear evidence of the existence of a supermassive black hole in the centre of our galaxy. Regardless of the big extinction of light in the direction of Sgr A*, we have been able to constrain very accurately the physical parameters of this object in the past decade through observations in the proper wavelengths; even more with the advent of adaptive optics and the collaboration of various institutes and researchers around the world. Understanding the mechanisms responsible for the existence of S stars around the BH is definitely a purpose of ongoing research and it would teach us much more about supermassive black holes and star formation in the Universe.

References

[1] Schodel et. al. 2002, Nature "*A star in a 15.2 year orbit around the supermassive black hole at the centre of the Milky Way*" `https://arxiv.org/abs/astro-ph/0210426`

[2] Ghez et al. 2008, ApJ, 689, 1044 "*Measuring distance and properties of the Milky Way's central supermassive black hole with star orbits*"

[3] Eisenhauer et al. 2005, ApJ, 628, 246. "*Sinfoni in the galacitc center: Young stars and infrared flares in the central light-month*"

[4] Gillessen et al. 2009, ApJ, 692, 1075 "*Monitoring stellar orbits around the massive black hole in the galactic center"*

[5] `https://downloads.rene-schwarz.com/download/M001-Keplerian_Orbit_Elements_to_Cartesian_State_Vectors.pdf`

[6] `https://www.nasa.gov/`