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The central black hole in the Milky Way: the history of the Nobel Prize 2020

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In 2020, the Nobel Prize in Physics was awarded to the German astronomer Reinhard Genzel and to the American astronomer Andrea Ghez; astronomers highly acclaimed for their work in ground-based observations at large telescopes. The prize was awarded "for the discovery of a supermassive compact object at the center of our Galaxy". In fact, they, with their colleagues, have obtained net evidences in favour of a supermassive black hole in the center of the Milky Way. This review presents the main points of their 30-year fruitful quest.

Keywords: Galaxies: evolution; black holes: masses

1 Introduction

In 2020, the Nobel Prize in physics was divided, one half was awarded to the physicist Roger Penrose and the other half jointly to the astronomers Reinhard Genzel and Andrea Ghez. The theoretical part contained the proof that the existence of black holes was a net consequence of the general theory of relativity, and it was a rather ancient discovery. But the experimental part – "the discovery of a supermassive compact object at the centre of our Galaxy" – is a quite modern, very high-technology work. It was completed during the last 30 years at the largest telescopes of the world, and became successful due to two main technological breakthroughs: near-infrared imaging detectors and adaptive optics.

Panoramic astronomical observations of the Galaxy center were difficult, almost impossible until the beginning of the 1990s. Because of the position of our Sun within the thin Galactic disk, we look at the Galaxy center through the 8-kpc slab of dust. The extinction to the Galaxy center in the optical light is immense, up to 25–30 mag. But it becomes much less if we move into the near-infrared (NIR) spectral range, for example, at $\lambda = 2.2\,\mu$m where the Earth atmosphere is rather transparent, the extinction toward the Galactic center is only 2.7 mag [1], and many bright stars there are well

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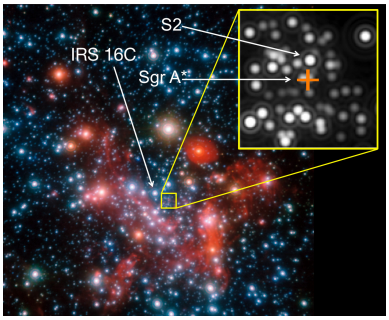


Figure 1 The combined-colour H/K/L′ image of the Milky Way center. The total field of view is about 20″, the spatial resolution is 0.04″. The star S2 which is the closest to Sgr A* is shown by an arrow at the insert. The image is obtained with the adaptive-optics bonnet NACO at the VLT. The figure is taken from the ESO public gallery, credit: ESO/MPE/S. Gillessen et al.

seen in the NIR. They were strongly crowded in the very center (Fig. 1), so another technological condition to observe the Galactic center effectively was to improve the spatial resolution of observations. In the NIR, the highest possible diffraction-limited resolution at the 8–10-m class ground-based telescopes, 0.05–0.1″, was achieved initially with the speckle imaging techniques in combination with the first panoramic, 256×256, NIR detectors [2, 3, 4], and later by using adaptive optics which allow us to correct atmospheric wave distortions in real time through monitoring a nearby bright star [5, 6, 7] or later a special laser artificial star.

One of the most ambitious aims of the Galactic center observations was to catch star motions in the vicinity of the proposed central black hole. Its presence in the Galactic center was suspected for a long time, because a very compact radiosource, Sgr A*, was observed there [8], and the estimates of its extension obtained with the Very-Large Baseline Interferometer (VLBI) gave only an upper limit: <400 μas [9, 10]. Gaseous clouds moved very quickly in the vicinity of Sgr A* implying the enclosed mass of 2–4 million solar masses [11, 12, 13, 14]. Since the Sgr A* was a radiosource which was not seen in other electromagnetic waves (X-ray, UV, optical, NIR...) this "dark gravitating object" was the first candidate for supermassive black holes. However these early dynamical estimates, even though everyone believed in circularity of gas rotation around the Galactic center, left room for a possible cluster of dark remnants of stellar evolution due to their poor spatial resolution. Only the works by R. Genzel with colleagues and by A. Ghez with colleagues having studied stellar motions very close to Sgr A* could confirm with confidence that this "dark gravitating object" is certainly a black hole.

2 NIR speckle and adaptive optics: the orbit of the star S2 closed around Sgr A*

The research work for which the Nobel Prize was awarded was started in 1992 by Reinhard Genzel with colleagues at the European Southern Observatory and in 1995

by Andrea Ghez with colleagues at the 10-m Keck telescope. Both groups used initially the speckle interferometry techniques.

The European team observed then at the 3.5-m New Technology Telescope (NTT) the design of which provided good stable seeing during exposures. Between 1992 and 1997 five epochs were fixed, and deep images of about 600 stars located within the radius of 0.5 pc from Sgr A* with the K-band limit of 15–16 mag were obtained. The astrometric accuracy achieved was about 0.15 arcsec. For 39 stars certain position shifts were detected [15], and the radial trend of stellar velocity dispersion was calculated between $R \approx 0.05$ pc and $R \approx 0.5$ pc, under the assumption of isotropic velocity ellipsoid [16]. This trend was well fitted by a Keplerian law, $v \propto R^{-1/2}$ that implied a point-like central mass concentration of 2.6×10^6 solar masses within one light-week of the compact radio source [17]. The conclusion about the supermassive black hole in the center of the Milky Way was "hard to escape" [17].

The American team started 3 years later, and between 1995 and 1997 they had fixed only three epochs; but they had a much larger telescope, the 10-m Keck one. They reached the K-band limit of 17 mag, and have measured proper motions for 90 stars improving then the accuracy of stellar velocity dispersion by a factor of 4 [18]. However, with this higher accuracy, Ghez et al. [18] had again obtained a Kepler-like decrease of stellar velocity dispersion with the radius, $\sigma_v \propto R^{-0.5\pm0.1}$, and the mass of the central dark object of 2.6 ± 0.2 million solar masses. The new important result was that the centroid of the stellar velocity dispersion distribution coincided with the Sgr A* within $\pm 0.1''$, so the central black hole settled just in the dynamical center of the Galaxy.

In 2000 Andrea Ghez with colleagues proposed a new approach which consisted of probing individual orbits for the bright stars the closest to the Sgr A*. By analysing position shifts of the stars over the temporal base of 1995–2000, they have found curved trajectories for three stars within 0.005 pc from the Sgr A* [19]; among those there was a famous S2 whose orbital period was then estimated as 15 years (Fig. 2).

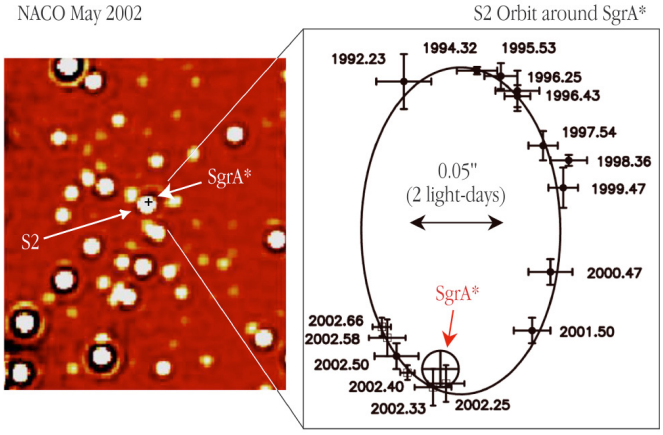


Figure 2 The star S2 and its orbit around the Sgr A* which was traced by both teams. The observations were started from 1992. The figure is taken from the ESO public gallery, credit: ESO.

The idea seemed to be very fruitful. In 2002, both teams observed already with adaptive optics. The team led by Genzel, working at the European Southern Observatory, had moved from the 3.5-m NTT to the 8.2-m VLT, and the spatial resolution of their imaging had been improved dramatically. They [20] had confirmed the "acceleration'" of the three stars, S1, S2, and S8, and had stated that their orbits were highly inclined, by 60°–80°, and eccentric, with $0.4 < e < 0.95$. The orbital period of S2 which had just reached its pericenter was estimated as 15.2 years, and the star had passed its pericenter in only 17 light-hours from the Sgr A* [21]. The estimate of the central gravitating mass was corrected to $3.7 \pm 1.5 \times 10^6$ solar masses by using only 2/3 of the S2 elliptical orbit. Till 2003, the Genzel's team found "accelerations" in the proper motions of six stars [22]; four stars passed their pericenters, and all of them kept Sgr A* in the focus of their orbits. Till 2005, the Ghez' team [23] found "accelerations" for a dozen of stars, and seven orbits including S2 were traced accurately with adaptive optics *and* spectral radial velocity estimates at the 10-m Keck telescope. The star S16 was caught in May 2000 in its pericenter in only 45 AU from Sgr A* with a spatial velocity of 12000 km/s, and the radius enclosing the gravitating supermassive dark object was reduced to 10 AU. Spectral data were involved in the orbit analysis by the Genzel' team from 2000 and by the Ghez' team from 2003. The high signal-to-noise NIR spectrum of S2 analysed by Ghez with colleagues in 2003 [24] had revealed that S2 is a massive star, with $M \approx 15$ solar masses, belonging to the spectral type of O8–B0, at the main sequence. The very existence of such massive, young ($T < 10^7$ years) stars in the nearest vicinity of the supermassive black hole is a puzzle till now. In 2007, the elliptical orbit of S2 was closed (Fig. 3). The event was fixed by a paper of Ghez with colleagues [25] where with all new astrometric and velocity data for S2 the estimate of the central black hole mass was shifted to 4.1×10^6.

After the first pericenter passage by the star S2, no doubts remained that "a supermassive compact object at the centre of our Galaxy" was in fact a supermassive black hole. The necessity to lock four million solar masses into the area with the radius of 10 AU constrained strongly the nature of this matter concentration. Usual astrophysical clusters – those of neutron stars, brown dwarfs, and other stellar remnants – suffer instability and are too short-lived with similar density [23, 26]. Even hypothetical fermion balls do not survive in such conditions [23, 27]. Reinhard Genzel mentioned in his Nobel Prize lecture that only a cluster of mini-black holes cannot be excluded due to its large relaxation and collapse time. However, in any case the existence of black holes became evident.

After 2008, the team of Andrea Ghez continued to improve their techniques at the 10-m Keck telescope. From 2009, the integral-field spectrograph OSIRIS began to operate allowing them to obtain kinematical information for many stars over extended fields of view. The main direction of further searches was to find more stars with short orbital periods and peri-passages close to Sgr A*. In 2012, the finding of S0102 with the orbital period of 11.5 years was reported [28]. Later, another star, S038, with the orbital period of 19 years, was traced from its apocenter almost to the peri-passage, and the central black hole mass was refined to $4.02 \pm 0.16(stat) \pm 0.04(sys)$ million solar masses while the distance to the Galactic center from the three-dimensional star motion along the orbit was estimated as $7.86 \pm 0.14(stat) \pm 0.04(sys)$ kpc [29].

The team of Reinhard Genzel increased also the number of traced stellar orbits:

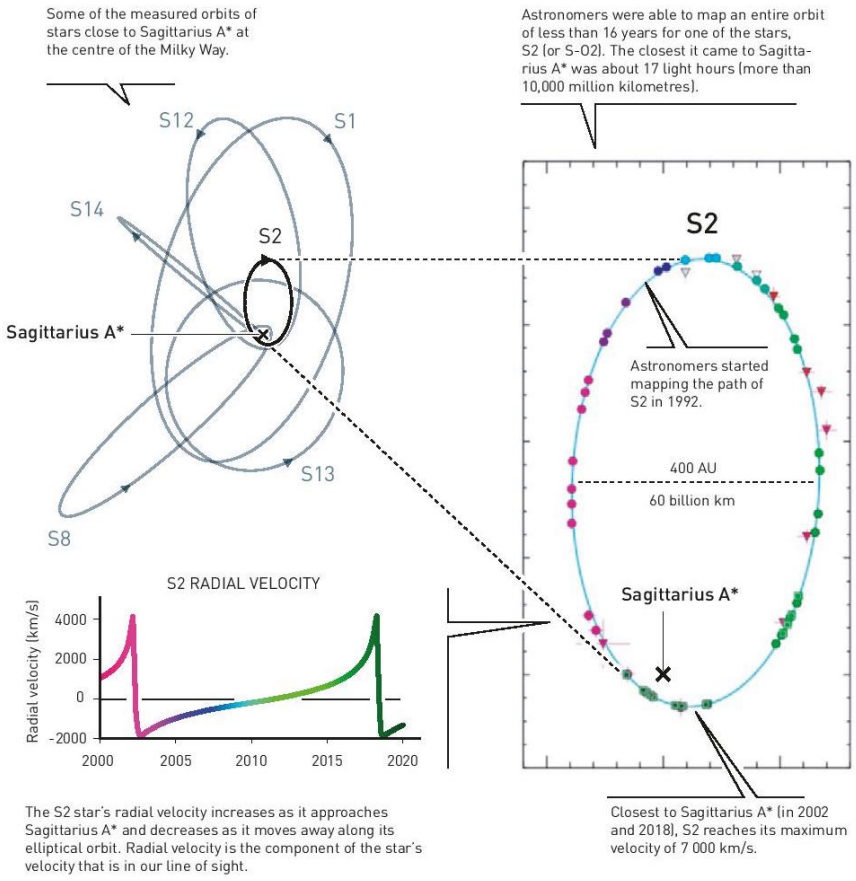


Figure 3 The orbit of the S2 star closed around Sgr A* which was traced by both teams among other traced individual stellar orbits. The S2 radial velocities are coded by colour in every point of the orbit. The figure is taken from the press-release of the Nobel Prize Committee. Credit: Johan Jarnestad/The Royal Swedish Academy of Sciences.

till 2017, they have analysed together 17 orbits around Sgr A* and have derived $4.28 \pm 0.10(stat) \pm 0.21(sys)$ million solar masses for the black hole and $8.32 \pm 0.07(stat) \pm 0.14(sys)$ kpc for the distance to the Galactic Center [30]. Both teams worked in parallel independently, and the results were quite consistent!

3 The second round of S2 and the General Relativity

After 2002 when the first pericenter passage by S2 was traced, it became clear that the proximity of the star to Sgr A* at that moment and its immense velocity, up to 7650 km/s, provided an unique possibility to check the general relativity (GR) theory of gravitation. But to be able to test it, a much better accuracy, both astrometric and kinematical, was needed. While waiting for the next S2 pericenter passage in May

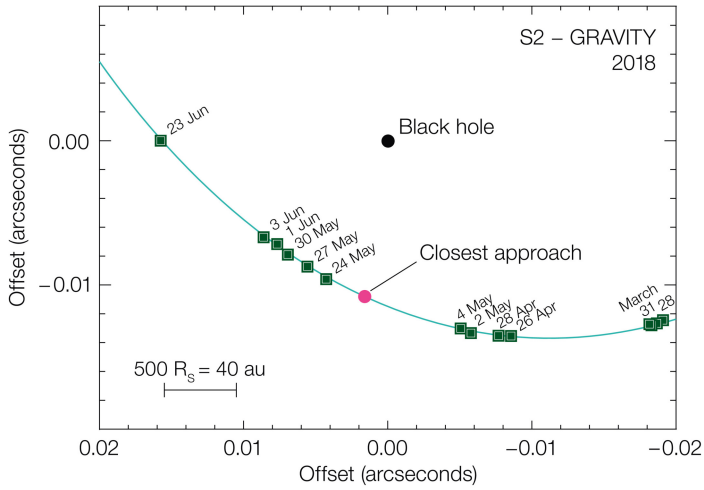


Figure 4 The pericenter passage in 2018 of the star S2 traced by the GRAVITY at the VLTI. The figure is taken from the ESO public gallery, credit: ESO/MPE/GRAVITY Collaboration.

2018, the European Southern Observatory designed new instruments which should enable astronomers to trace the S2 orbit with an accuracy higher by an order of magnitude than earlier. The improvement of the kinematical study was provided by the integral-field spectrometer SINFONI having started to operate at the VLT in 2004 [31]. The SINFONI operated with the adaptive optics-assisting curvature sensor and provided a full set of spectra for all the stars up to a limiting magnitude of $K = 16^m$ over the field of view $0.8'' \times 0.8''$ with the spatial resolution of 75 mas. The improvement of the astrometric accuracy was achieved through the NIR-light interferometry. A near-infrared cryogenic beam combiner instrument GRAVITY which was intended to acquire the light of all four 8.2-m telescopes of the VLT with the phase correction in real time was built starting from 2008 [32] and was installed on the site in July 2015. It promised a spatial resolution of $FWHM = 2 \times 4$ mas. In the eve of 2018 all was ready [33].

The goal of the experiment with the GRAVITY tracing the peri-passage by the star S2 was to search for the so-called first order Post-Newtonian effects (PPN1) of GR, namely the gravitational redshift and in plane orbital precession. The observations were started in March 2018 and lasted till the end of 2019. The positions of the S2 between the end of March 2018 and the end of June 2018 are shown in Fig. 4. Fourteen positions along the orbit were fixed with the GRAVITY accompanied by the 18 radial velocity measurements with the SINFONI.

The PPN1 effects have been certainly detected by the GRAVITY collaboration. At the moment of the closest approach of the S2 to the Sgr A*, on May 19th, 2018, its radial velocity exceeds the predictions of the Newtonian (Keplerian) mechanics fitted to the whole orbit traced in 1992–2017 by some 200 km/s corresponding to 5σ [34]. This deviation includes the combined effect of the gravitational redshift and of the transverse Doppler effect. The dependence of this deviation on the proximity to

the Sgr A* agrees perfectly with the prescriptions of the General Relativity for the gravitating black hole with the mass of 4 million solar masses. An analysis of the longer temporal range of the GRAVITY measurements which were finished last year has also confirmed the Schwarzschild precession of the S2 orbit: by comparing the half of the orbital ellipse *before* the peri-passage and *after* the peri-passage, the GRAVITY collaboration has found an orbit turn by 12′ per one orbital period [35]. And again, the quantitative result is in full agreement (within 19%) with the predictions of the classical GR.

4 The own radiation of Sgr A*

For a very long time the compact object in the dynamical center of the Galaxy was known only as a radiosource [8]. However, the observational techniques developed, and in the XXI century new facilities over the full electromagnetic spectrum became available. In particular, new high-resolution space telescopes observing in X-rays were built – the Chandra in U.S.A. and the XMM-Newton in Europe. And just immediately the Sgr A* was discovered in X-rays – though it appeared to be very faint in this spectral range. The first signal was detected by the Chandra: [36] reported the persistent signal from an unresolved compact source at the position of Sgr A* revealing a luminosity of 2×10^{33} erg/s in the spectral range of 2–10 keV. If the signal belongs to a black hole with the mass of 4 million solar masses, it is well below the Eddington luminosity, about $10^{-8} L_{edd}$ [37]. After that, regular X-ray flares were detected both by the Chandra and by the XMM-Newton, firstly in serependitious pointings [38, 39], and later during special monitoring long-lasting campaigns undertaken both with the Chandra [40] and with the XMM-Newton [41]. The typical rate of X-ray flares superposed onto the quiescent stable X-ray radiation was found to be one per day, with the amplitudes from 30–45 times (the most frequent level) to 160 times [39].

The NIR counterpart of the Sgr A* was discovered by the team of Ghez at the 10-m Keck telescope when the AO-assisted camera NIRC2 began to operate [42] and the star S2 left its orbit pericenter where it overshined Sgr A* in NIR: it became visible in the L′-band (3.8 μm) but still unseen in the K-band (2.2 μm). However, it appeared to be strongly variable: the NIR flares rising by a few magnitudes in some 8 min were soon discovered both in L′ [43] and in K [44]. As it was recognized later, the quiescent radiation of Sgr A* had a spectral energy distribution (SED) with the maximum at sub-millimeter wavelengths [45] and could be attributed to synchrotron radiation from a thermal population of electrons with $kT \sim$ 10–30 MeV accreting onto the black hole [37]. The accretion rate, however, is very low: the upper limit onto the Faraday rotation measurements obtained by [46] precludes the accretion rate larger than $2 \cdot 10^{-7}$ solar masses per year. But the SED of flares differs strongly from the SED of quiescent radiation, and their nature is still controversial. The first detection of the quasi-simultaneous flares in the NIR and in the X-rays on June 20th, 2003, was reported by the Genzel' team with the involvement of the Chandra's data [47]. Later the specialized multi-wavelength monitoring campaigns XMM-Newton+VLT or Chandra+Keck were undertaken [41, 48], or even XMM-Newton+VLT/NACO+APEX/LABOCA(870μm)+FERMI/LAT(0.1–

20 GeV) [49], and it was found, firstly, that the X-ray flares were much less frequent than the NIR-flares. Secondly, when there was an obvious matching between NIR and X-ray flares, they were not simultaneous. Early results gave evidence in favour of X-ray flare delays by a few to tens of minutes [49, 41], and then the model of inverse Compton scattering of NIR-flares occuring in the outer parts of accreting flow by hot electrons of the inner disk seemed to be preferable [50]. But later some flares were observed where the X-ray event was preceding the NIR flares [51]. Recent data of the longest, more than 100 hours, simultaneous IR and X-ray observation campaign with the Hubble Space Telescope and the Chandra indicates also that the X-ray may lead the IR by 10–20 minutes [48]. Then another model for the Sgr A* flares is required, and recently a model of strongly magnetized accretion flow with magnetic reconnection was proposed [52].

5 Summary

Although the citation of the Nobel Prize Committee applied to Reinhard Genzel and Andrea Ghez was rather cautious and had not included any mention of a black hole (perhaps, leaving room to award the further observations with the Event Horizon Telescope?), their works had indeed proved observationally the existence of supermassive black holes in galactic centers. Without any doubt, they are more than worthy to be awarded such a great prize.

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