Black Holes Are in Sight - Nobel in Physics 2020

G.C. Anupama

Indian Institute of Astrophysics, II Block Koramangala, Bengaluru 560034
Email: gca@iiap.res.in

G.C. Anupama is a Senior Professor at the Indian Institute of Astrophysics, Bengaluru. Anupama is an observational astronomer with research interests in the area of time domain astronomy. She has been working on studying the temporal evolution of supernova and nova outbursts, and understanding the physical conditions in these systems. Anupama has also been deeply involved in development of astronomical facilities in the country.

Abstract

The Nobel Prize in Physics 2020 has been awarded to three scientists. One half of the prize was awarded to Roger Penrose and the other half was jointly awarded to Reinhard Genzel and Andrea Ghez. Penrose's discovery of the singularity theorem showed black hole formation to be a robust prediction of the general theory of relativity, with these objects forming naturally in overdense regions. On the other hand, painstaking, independent studies of the motion of stars over nearly three decades by Genzel and Ghez led to the discovery of a supermassive compact object at the centre of our Galaxy, that can only be a black hole. More recent observations have enabled detection of the relativistic precession of the orbit of the star closest to the Galactic centre, the presence of massive young stars close to the supermassive black hole, and intriguing objects enshrouded in gas and dust in the innermost regions of the nuclear stellar cluster.

Introduction

The 2020 Nobel Prize in Physics has been awarded for "theoretical foundation for black holes and the supermassive compact object at the Galactic centre". One half of the prize goes to Roger Penrose (Oxford University) "for the discovery that black hole formation is a robust prediction of the general theory of relativity" and the other half jointly to Reinhard Genzel (Max Planck Institute for Extraterrestrial Physics [MPE]) and Andrea Ghez (University of California, Los Angeles [UCLA])" for the discovery of a supermassive compact object at the centre of our Galaxy". This supermassive compact object is compatible with a black hole. One may ask why this discovery is important? This is so because the central object shapes the way the Galaxy evolves. It is also important since these observations have paved the way for more sophisticated observations of the Galactic centre that enable precise tests of the general theory of relativity and its predictions. The 2020 Nobel in Physics is particularly special as Andrea Ghez is the fourth woman ever awarded a Nobel in Physics.

In this article, we will briefly discuss the concept of black holes, the basic idea behind the observations that led to the discovery of a supermassive black hole in the Galaxy, the techniques used, and then provide a brief overview of the current status.

What are black holes?

The concept of "dark stars" was first proposed by John Michell (in 1783) and Pierre-Simon Laplace (in 1786) as objects that, when compressed to a sufficiently small size, would have a strong gravitational pull leading to an escape velocity exceeding the speed of light. Such objects would absorb all the light that hit it and reflect nothing back. The use of the term "black hole", traced to Robert H. Dicke, was popularised by John Wheeler. Michell also speculated that one could infer the presence of the "dark stars" through the motions of a luminous body revolving around them. The teams led by Reinhard Genzel and Andrea Ghez have precisely inferred this about the centre of the Milky Way galaxy through their observations.

Black holes are regions of space-time where matter is densely compacted to such an extent that it traps matter, and even photons and does not let them escape. The boundary of this region, called the "event horizon" has an enormous effect on the fate of an object crossing it. Long considered a mathematical curiosity, the theoretical work in the 1960s showed them to be a generic prediction of general theory of relativity.

Stellar mass black holes form during the collapse of very massive stars collapse at the end of their life cycle. Once a black hole has formed, it can continue to grow by accreting mass from its surroundings. Through the accretion of other stars and merger with other black holes, supermassive blackholes (mass $\geq 10^6$ $M_\odot$) may form. Although black holes cannot be directly observed, their presence can be inferred through their effect on their surroundings. Matter falling onto a black hole can form an accretion disc that, heated by friction, radiates. Stars passing too close to a black hole can be shred into streamers, or tidally disrupted, shining brightly before being devoured. The dynamics of stars around a black hole can provide information about its mass and location.

The discovery of quasi-stellar objects (quasars or QSOs), and their identification as being extragalactic sources at cosmological distances implied extremely high luminosities (over a trillion times that of our Sun, from a region about the size of our Solar System). Observations of rapid, aperiodic time variation of the emission on time-scales of days, or even hours indicated a small and powerful source of energy. The only mechanism that can produce such enormous amounts of energy is by conversion of gravitational energy into light by a supermassive black hole. The observations of several quasars with the Hubble Space Telescope showed quasars resided in the centres of galaxies.

Lynden-Bell and Rees [1], extrapolating the idea that the highly energetic phenomenon observed in active galactic nuclei (such as quasars) are powered by the central massive black hole, suggested that even the lesser active galaxies, such as our own Milky Way, may also harbour a massive central black hole, that could be dormant. They also suggested various types of observations that could test the validity of this idea.

Hubble Space Telescope observations have been fundamental in the study of black holes, and providing strong evidence for presence of black holes at the centres of large and even small galaxies. These studies have also indicated that larger galaxies are hosts to more massive black holes implying that there must be a link between the formation of a galaxy and its black hole (and probably vice versa). This has implications for the theories of galaxy formation and evolution, an extremely important and active area of research in astronomy.

At a distance of ~ 8 kpc (1 parsec (pc) = 3.086×10^{13} km or 3.26 ly), the Galactic centre is the closest galactic nucleus, and provides a unique laboratory to study the physical processes in the centre of a galaxy with the highest angular resolution possible.

The centre of the Milky Way Galaxy

The centre of our Milky Way galaxy, or the Galactic centre, is the rotational centre of the Galaxy. It is located roughly 26,000 ly from the Solar System, in the direction of the Sagittarius constellation. Absorption due to interstellar dust along the line of sight makes it difficult to see the centre in visible, UV or soft X-ray wavelengths. It is, however, observable in the infrared, radio and X-ray wavelengths. Observations in these bands have revealed the presence of a complex radio source located very close to the Galactic centre. This radio source contains an intense, compact radio and X-ray source Sagittarius A* (Sgr A*) (Figure 1). This source has a non-thermal spectrum, compact size, and lack of any detected motion, based on which astronomers associate it with the central black hole.

A definite proof for the existence of the central black hole, and its association with Sgr A* lies in the distribution of mass in the central few pc of the Galaxy. The motion of the stars in the vicinity of this black hole reveals the mass interior to their orbital radius, if gravity is the dominant force (as expected for a central black hole). The velocities of the stars for a Keplerian orbit around the central object would be proportional to $1/r^2$ for a star at distance r. Keplerian orbits are not expected if the central object is due to a cluster of stellar mass objects. Velocities of the stars closest to the Galactic centre thus provide the strongest constraints on the black hole hypothesis.

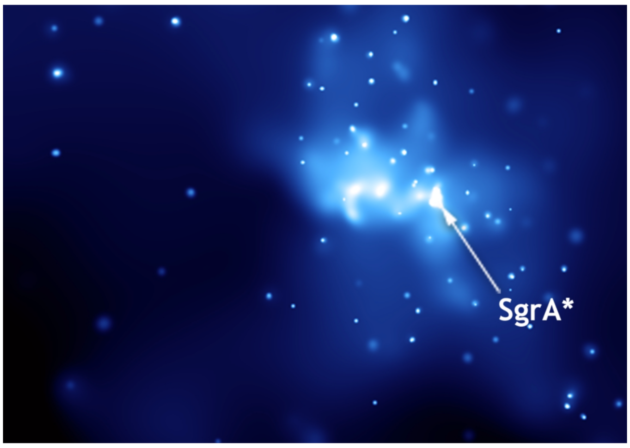


Figure 1: *Galactic centre region. (Figure Source: Wikipedia)*

Stellar motions in the Galactic Centre

The motions of stars orbiting the Galactic centre have been monitored for over three decades by two observational teams, one led by Genzel, and the other by Ghez. While Genzel's group used the telescopes in Chile operated by the European Southern Observatory (ESO), Ghez's group used the Keck Observatory in Hawaii.

Resolving individual stars in the very crowded region of the Galactic centre requires very high spatial resolution. Further, obscuration by interstellar dust limits observations at optical wavelengths. Therefore, observations were carried out in the near-infrared, in the K-band, centred at 2.2 μm where the interstellar extinction is reduced by a factor 10 compared to the optical. Spatial resolution was obtained by the use of *speckle imaging* initially, and *adaptive optics* subsequently.

Speckle imaging

Turbulence in the Earth's atmosphere causes a distortion in the wavefront of the light from the distant sources. This distortion, termed as "seeing" causes the images of point sources, such as stars, to break into speckle patterns that change rapidly over time-scales shorter than 1 s. Long exposures thus result in a blurred image of the point source. The technique of speckle imaging involves obtaining a series of very short exposure images such that speckle patterns of the point sources are imaged (Figure 2). The images are then stacked using the shift and add method. In this method, one of the frames is chosen as the reference frame. All frames are then aligned with respect to the brightest speckle in the brightest source in the frame, and co-added. Diffraction limited images are thus obtained, providing good spatial and angular resolution.

Using ESO's 3.5 m New Technology Telescope (NTT), Genzel's group determined the proper motions of 39 stars between 0.03 and 0.3 pc from Sgr A* [2]. Using the 10 m Keck I telescope, Ghez's group studied the proper motions of 90 stars [3]. Both groups used the method of speckle imaging.

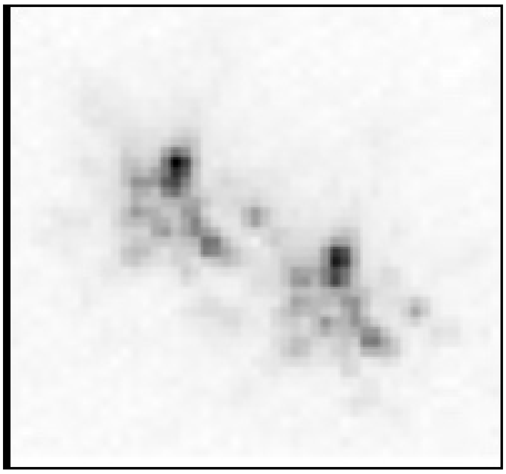


Figure 2: *Speckle images of a binary star system (Figure Source: Wikipedia)*

Adaptive Optics

The method of speckle imaging limited the studies to only the brighter stars due to the short exposure times. This was overcome with the use of adaptive optics. Adaptive optics is the technique of real-time correction of the distortions caused by the turbulences in the Earth's atmosphere by the use of computer controlled deformable mirrors. This technique requires a bright reference star close to the object being observed. In regions where a bright "natural star" is not available, an artificial star can be created by laser excitation of sodium atoms in the upper atmosphere. This reference source is used to measure the blurring caused by the local atmosphere, which is then corrected for by the deformable mirror that changes shape to compensate for the aberrations. The compensation is done in real-time using a feedback loop, enabling long exposures. Thus shaper deeper images can be obtained (Figure 3).

Data obtained using adaptive optics provided positional accuracies that were better than a factor ~ 6 compared to that obtained with speckle imaging. Further, since this technique allows longer exposures, it was also possible to obtain spectra of the stars in the Galactic centre, which were used to study measure the radial velocities of the stars, as well as their composition.

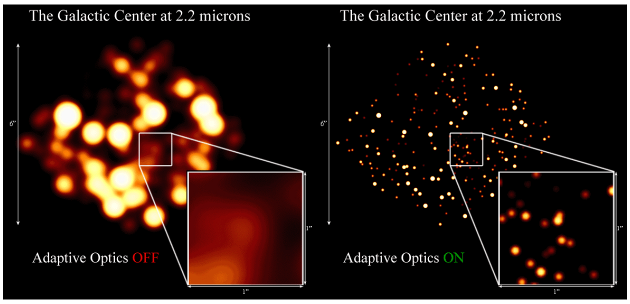


Figure 3: *Sharper, deeper images of the Galactic centre with adaptive optics. (Figure credit: UCLA Galactic Center Group - W.M. Keck Observatory Laser Team)*

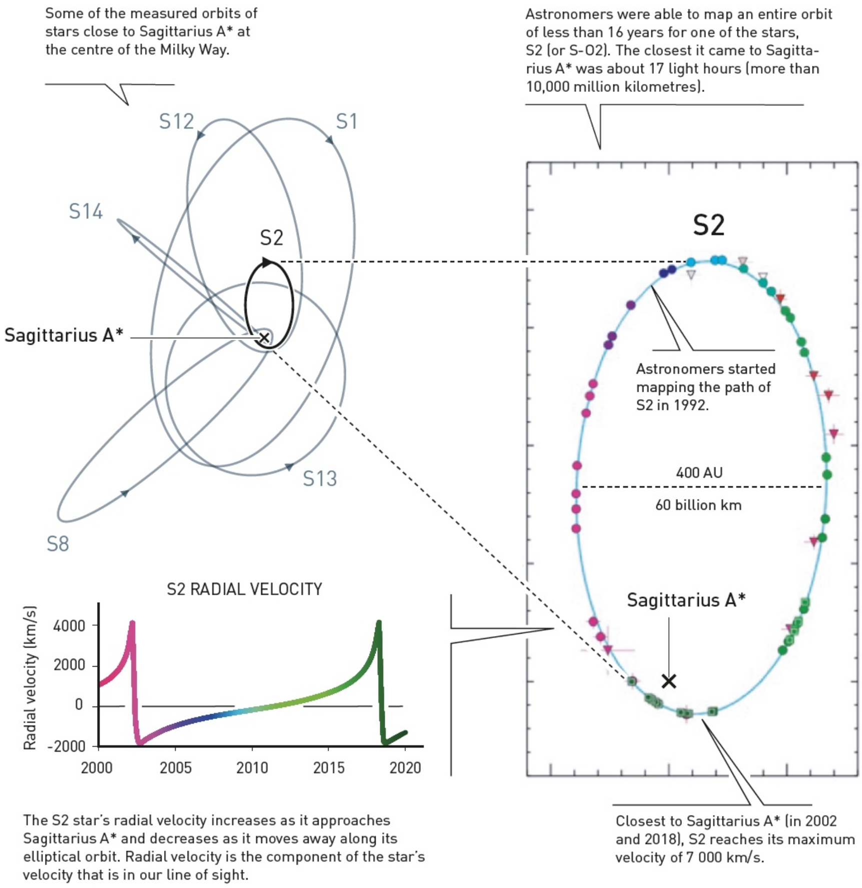
Discovery of the supermassive black hole

The distribution of the velocity of the stars in the Galactic centre region were found to be non-uniform. About 11 sources, with the highest velocity were found clustered towards the field centre [3]. Of these, seven had velocities exceeding 500 km s^{-1}, and appeared to be members of the central Sgr A* cluster. The coincidence between the peak of the stellar surface density, the peak of the velocity dispersion with the nominal position of Sgr A* suggested the dynamical centre of the Galaxy was indeed Sgr A*. Both studies found an apparent isotropy of the stellar velocity field suggesting the stars were moving under the influence of a spherical potential. Further, the projected stellar velocity dispersion as a function of the projected distance from Sgr A* was found to be consistent with Keplerian motion, and that the gravitational field was dominated by a mass within 0.1 pc [3,4].

The study of the stellar orbits indicated one of the stars, labelled S2 by Genzel's group and S0-2 by Ghez's group, had a very short orbiting period around Sgr A*, just under 16 years [5,6]. The Sun, for example, takes over 200 million years to complete a full orbit around the Galactic centre. S2/S0-2 has a highly elliptical orbit, with eccentricity $e = 0.88$. For a black hole mass of 4×10^6 $M_\odot$, S2/S0-2 has a pericentre distance of just about 17 light hours, and its orbital plane is inclined by about 46° with respect to the plane of the sky.

There is excellent agreement between the data obtained by the two groups, and the combined work established the Galactic centre contains a highly concentrated mass of 4×10^6 $M_\odot$ within the pericentre of S2/S0-2, and located within 2 mas of Sgr A*. A robust interpretation of the observations is that the compact object at the centre of our Galaxy is a supermassive black hole. This is substantiated by the non-thermal radio emission, near-infrared and X-ray flares detected from the same position. Figure 4 provides a pictorial summary of the determined orbits for stars closest to Sgr A*. The orbit of S2/S0-2 based on data since 1992 is shown along with its radial velocity.

The orbits of the stars in the Galactic cluster have now been studied for over two decades at the highest angular resolution


Some of the measured orbits of stars close to Sagittarius A* at the centre of the Milky Way.

Astronomers were able to map an entire orbit of less than 16 years for one of the stars, S2 (or S-02). The closest it came to Sagittarius A* was about 17 light hours (more than 10,000 million kilometres).

Astronomers started mapping the path of S2 in 1992.

The S2 star's radial velocity increases as it approaches Sagittarius A* and decreases as it moves away along its elliptical orbit. Radial velocity is the component of the star's velocity that is in our line of sight.

Closest to Sagittarius A* (in 2002 and 2018), S2 reaches its maximum velocity of 7 000 km/s.

Figure 4: Orbits of stars near the Galactic centre. Orbit of S2/S0-2 based on data since 1992 is shown, as also its radial velocity. (Figure courtesy: The Royal Swedish Academy of Sciences)

possible with the current facilities. Stellar orbits in the central 1.0 × 1.0 arcsec, based on data obtained by the UCLA Galactic Center Group using the Keck telescopes are shown in Figure 5. Improved, well measured astrometric positions have enabled measurement of proper motions, accelerations and orbits for nearly 1150 stars [7]. 24 stars are detected to be accelerated due to the influence of the SMBH. The GRAVITY collaboration [8] have carried out interferometric imaging and astrometry using the four ESO/VLT telescopes, and have achieved an angular resolution that is about 100 times sharper than the first speckle images. The improved, more precise astrometry for S2/S0-2 has not just provided kinematic evidence for a compact object in the Galactic centre, but also very high precision estimate of the distance to the Galactic centre. The 2018 pericentre of S2/S0-2 led to the detection of relativistic corrections needed to model the orbit of the star.

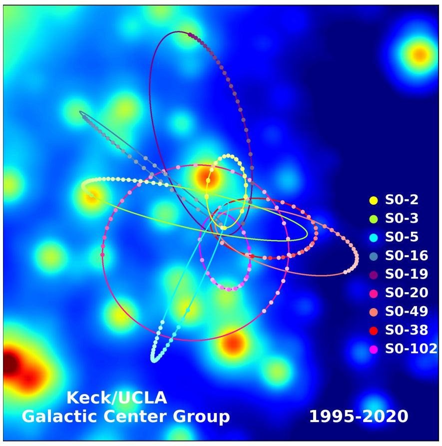


Figure 5: The stars within the central 1.0 × 1.0 arcsec of our Galaxy. The best fitting orbital solutions to the annual average positions are shown for each star. (Figure credit: UCLA Galactic Center Group - W.M. Keck Observatory Laser Team)

The diffraction-limited imaging and spectroscopic observations of stars in the Galactic centre cluster over the past two decades have transformed our understanding of the centre of the Milky Way. To summarise, these observations have (a) established the existence of a supermassive black hole in the centre of our Galaxy, (b) detected relativistic red-shift of S2/S0-2 during its closest approach, providing the first test of General Relativity around a supermassive black hole.

The Galactic centre stellar population

The Milky Way nuclear star cluster consists of tens of millions of stars, densely packed in a small region around the

Galactic centre. This star cluster is mainly composed of a massive old stellar cluster. However, the centre of the cluster (within the central 0.5pc) shows a concentration of young stars (of age 4–6 Myr). Within this young stars population, there appears to be three dynamical categories: (1) a clockwise rotating disc ranging from 0.03 pc to at least 0.5 pc with moderate eccentricities, (2) an off-the-disc population in a more isotropic distribution over the same distances, and also with moderate eccentricities, and (3) within 0.03 pc of the black hole with high eccentricities of ~ 0.8, comprising of ~ 10 % of the young population. The presence of a young population of stars in the nuclear cluster is intriguing as the tidal force due to the supermassive black hole would suppress the formation of stars in the vicinity. Yet another intriguing aspect of the Galactic centre stellar population is the dearth of old red giants around the black hole.

The nuclear cluster stars cover ages of few Myr to several Gyr. Most of the stars are more than 5 Gyr old, with metallicities ranging from sub-solar to super-solar. The metallicity of a star is the chemical abundance of all elements heavier than hydrogen and helium. Since all elements are formed in the stars during nucleosynthesis, metallicity is also an indication of the age of the stellar population. A higher metallicity would indicate that stars formed from material that was already enriched with the heavier elements, and hence a younger population. On the other hand, lower metallicity would indicate an older population of stars that was formed out of material that was not contaminated by nucleosynthetic material. The formation and history of the nuclear star cluster can be understood by the study of the kinematics and chemical abundances (chemo-dynamics) of the stars in the cluster. Recent chemodynamic studies of stars in the inner 1pc of the nuclear cluster have shown evidence for the presence of two kinematically and chemically distinct components [9]. The majority of the stars belong to a super-solar metallicity component with a rotation axis perpendicular to the Galactic plane. In addition, there is also a kinematically distinct sub-solar metallicity component that contains about 7% of the stars. This component appears to be rotating faster than the main component with a rotation axis that may be misaligned. It is speculated that this component could be an infalling star cluster, or a dwarf galaxy that has merged with the nuclear star cluster, although observations favour the former.

A new class of objects have been discovered in the Galactic centre, named as G objects. While the first of these objects, G1 and G2 were discovered nearly two decades earlier (G1 in 2005 and G2 in 2012), four more were discovered very recently, and labelled G3-G6 [10; and references therein]. All these objects are found to lie within 0.04 pc of the black hole. The nature of these objects is not very clear. While they show characteristics of gas and dust clouds, their dynamical properties are similar to stellar-mass objects. The orbital periods range from 100 y to 1000 y. While G1 and G2 have very similar orbits, the rest have very different orbits (Figure 6). G2 made its closest approach to the central black hole in 2014, when it showed a very peculiar behaviour. From being a compact object, it got elongated at closest approach, clearly indicating tidal interaction with the black hole. In subsequent observations, post 2014, the object appeared to be regaining its compact nature. This implies that the object consists of a central compact source enshrouded in a cloud of gas and dust that was tidally disrupted during closest approach. Ciurlo et al. suggest binary mergers as the origin of the population of the G objects.

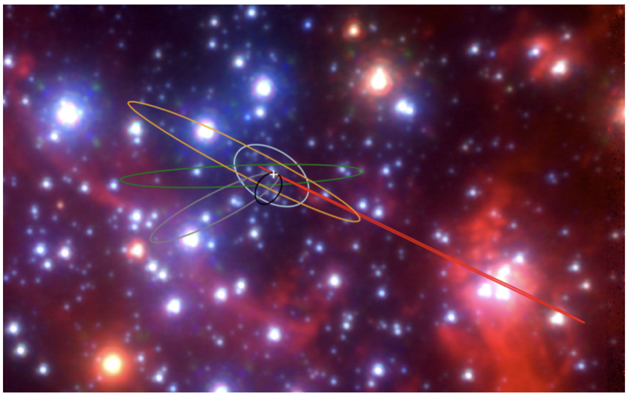


Figure 6: The orbits of the G objects around the Galactic centre, marked as cross. (Figure credit: Anna Cirulo/Tuan Do/UCLA Galactic Center Group)

The nuclear cluster stellar populations provide with different probes of the physical conditions near a supermassive black hole. Their study has implications for black hole growth as well as the inward migration of compact objects.

Future frontiers

The Galactic centre, located at just 8 kpc from us presents a unique opportunity to study fundamental physics of supermassive black holes and their roles in the formation and evolution of galaxies. The current 10m class telescopes equipped with adaptive optics and/or interferometric capabilities have already transformed our understanding of the Galactic centre. The high angular observations have enabled accurate determination of the proper motion of stars within 0.04 pc of Sgr A*, established the presence of a supermassive black hole at the centre and provided the first test of General Relativity around a supermassive black hole. They have shown the existence of stellar populations that cannot be easily explained by our current understanding of star formation in a black hole environment. Additional progress, however, is now limited by the tremendous source confusion present within the angular resolution of the current measurements.

The next generation of extremely large telescopes (ELTs), such as the Thirty Meter Telescope (TMT) that India is a partner in, will have a much better angular resolution. The gain in resolution and contrast with the TMT will enable detection and mapping of the orbits of stars much closer to the centre (Sgr A*) and also much fainter (by about 4 magnitudes) than currently possible. The measurement of orbits of the closer, short period stars will enable measurement of the precession of the periapse and test the specific metric form of General Relativity, probe the distribution of dark stellar remnants and dark matter around black hole and test the models of galaxy evolution and dynamics. The observations will supplement the theoretical studies, providing a great fillip to black hole science. They will also, hopefully, provide answers to the outstanding puzzles on the origin of the nuclear massive young star cluster, whose formation should have been suppressed by the central supermassive black hole, and an unexpected dearth of old red giants around the supermassive black hole.

A more recent advancement in the observations of supermassive black hole in a galactic centre has enabled probing closer to the black hole event horizon. This is the remarkable image of the centre of the galaxy M87 obtained by the Event Horizon Telescope (EHT). An EHT image of Sgr A* will enable study the predictions of General Relativity from yet another perspective.

Acknowledgements

This article has made use of the images (Figure 3 and Figure 5) created by Prof. Andrea Ghez and her research team at UCLA and are from data sets obtained with the W. M. Keck Telescopes, and downloaded from http://www.astro.ucla.edu/ ghezgroup/gc/images.html.

References

1. D. Lynden-Bell and M. Rees, MNRAS, **152**, 461 (1971)
2. A. Eckart and R. Genzel, Nature, **382**, 47 (1996)
3. A.M. Ghez, B.L. Klein, M. Morris, E.E. Becklin, ApJ, **509**, 678 (1998)
4. A. Eckart and R. Genzel, MNRAS, **284**, 576 (1997)
5. R. Schödel et al., Nature, **419**, 694 (2002)
6. A.M. Ghez et al., ApJ, **586**, L127 (2003)
7. S. Jia et al., ApJ, **873**, 9 (2019)
8. GRAVITY Collaboration: R. Abuter et al., A&A, **615**, L15 (2018)
9. T. Do et al., ApJ, **901**, L28 (2020)
10. A. Ciurlo et al., Nature, **577**, 337 (2020)