BIUST Teaching, Research, & Innovation Symposium 2023 (TRDAIS 2023)
Botswana International University of Science and Technology
Palapye, Botswana, 18 - 19 September 2023
ISSN: 2521-2293

Seeing the Galaxy's central black hole with the Africa Millimetre Telescope

Rhodri Evans[1], Michael Backes[2], Heino Falcke[3], and Marc Klein-Wolt[4]

[1]Department of Physics and Astronomy, Botswana International University of Science and Technology. email: evansr@biust.ac.bw
[2]Department of Physics, Chemistry and Material Science, The University of Namibia
[3,4]Department of Astronomy, Radboud University

28th October 2022

Abstract

Using very long baseline interferometry Astronomers are able to link together telescopes in different parts of the world to obtain incredible angular resolution of millionths of an arc second. The Event Horizon Telescope (EHT) is such a network, and this collaboration has recently published the first-ever images of the supermassive blackholes at the centre of Messier 87 and our own Milky Way. The Africa Millimetre Telescope (AMT) will be the first millimetre-wave telescope on the African continent, and will be an important addition to the EHT network. The AMT will improve the EHT's resolution, thus enabling us to better understand these strange but important objects. The AMT will be located in Namibia, and will see first-light in early 2024.

1 Introduction

The idea that there could be black holes at the centres of some galaxies was first proposed in 1964 by Seyfert [1]. He suggested that the intense emission coming from the active nuclei of some galaxies, Active Galactic Nuclei (AGNs), could be due to the accretion of material onto a central massive object [1]. This idea was further developed by e.g. Lynden-Bell and Rees [2], who proposed models where the prodigious energy output from quasars was be due to material accreting onto a central massive blackhole. In a prescient paper in 1974, Rees [3] further suggested that there could be a supermassive blackhole (SMBH) at the centre of *all galaxies*, not just AGNs. This prediction has been found to be true [4],[5],[6],[7].

In 1974, a compact radio source in the direction of the inner 1-pc core of the Galactic nucleus was first observed at 2.7 GHz and 8.1 GHz (Figure 1), using the Very Large Array (VLA) by Balick and Brown [8]. It was realised that this source, which has become known as Sagittarius A*, lies at the centre of our Galaxy, and this source has now been studied at many other wavelengths.

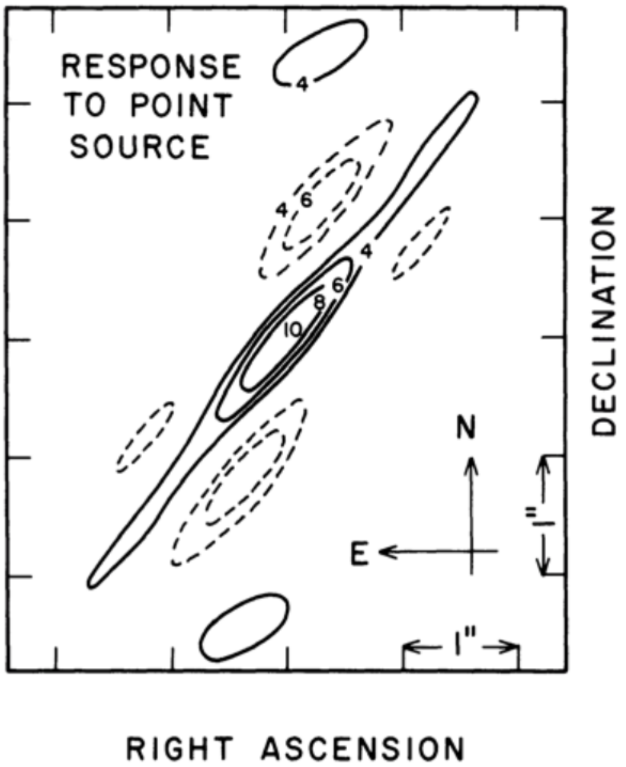


Figure 1: Sagittarius A* as observed at 2.7 GHz and 8.1 Gz ([8])

In the mid-1980s, a team at the Max Planck Institute for Extraterrestrial Physics (MPE)[9],[10] started making near-infrared observations of the motions of stars near Sagittarius A*. A second team, based at the University of California Los Angeles (UCLA), started a similar programme in the early-1990s [11],[12]. Observations by these two teams over several decades [13],[14] have enabled us to determine the mass of the central SMBH, it is found to have a mass of $M \approx 4.5 \times 10^6$ $M_\odot$ [13],[14]. Genzel and Ghez were awarded the 2020 Nobel Prize in Physics "for the discovery of a supermassive compact object at the centre of our galaxy"[15].

ISSN: 2521-2293

2 The Event Horizon of a black hole

Although General Relativity is necessary to correctly work out the details near the event horizon of a black hole, we can gain an idea of the size of the event horizon using simple Newtonian gravity. The event horizon is defined as the point where the escape velocity v_{esc} becomes equal to the speed of light c. The first solution of Einstein's field equations for a point mass were produced by Schwarzschild[16]. We therefore refer to the point in space where the event horizon is found as the *Schwarzschild radius* R_s.

Using Newtonian gravity, we can show that the escape velocity from any object is given by

$$v_{esc} = \sqrt{\frac{2GM}{R}} \tag{1}$$

where G is the universal gravitational constant, M is the mass of the object from which we are trying to escape, and R is radius we are considering. For a black hole, as $v_{esc} = c$ at R_S, so we can write

$$R_S = \frac{2GM}{c^2} \tag{2}$$

Although we cannot, by definition, observe the event horizon, we can observe light which passes very close to the event horizon[17]. The first person to do calculations of how light passing near a black hole would be bent was Hilbert in 1917[17]. Bardeen[18] calculated the geometrical properties of a rotating black hole's "shadow" against a bright background. Falcke, Melia and Agol[19] showed that an accreting black hole embedded in a plasma that is optically thin at millimetre wavelengths would produce a bright ring of emission, with a dim "shadow" created by the black hole's event horizon in its interior. They went on to suggest that such a shadow, while subtending too small an angle to observe conventionally, may be detectable towards the Galactic centre using the technique of very long baseline interferometry (VLBI).

Using the mass of the SMBH at the Galactic centre, we can calculate that the event horizon should have a physical diameter, using Equation (2), of $2R_S = 2.67 \times 10^{10}$ m. With the Sun lying 8 kpc [20] from the Galactic centre, this means that the event horizon subtends an angle of $\theta \sim 22$ micro arcseconds.

Such a tiny angle is *only* accessible using VLBI, where telescopes are linked together and make observations simultaneously. Although VLBI has been used for many decades at radio wavelengths, to achieve a resolution of a few tens of micro arcseconds would require baselines of millions of kms, which is currently not achievable. However, at millimetre wavelengths, the baseline of the Earth is sufficient, and therefore the Event Horizon Telescope (EHT) was conceived in 2009[21] to be a network of millimetre-wave telescopes spread across different continents. In 2017, the network comprised millimetre-wave telescopes in Europe, the continental USA, Mexico, Hawai'i, the South Pole and Chile (Figure 2).

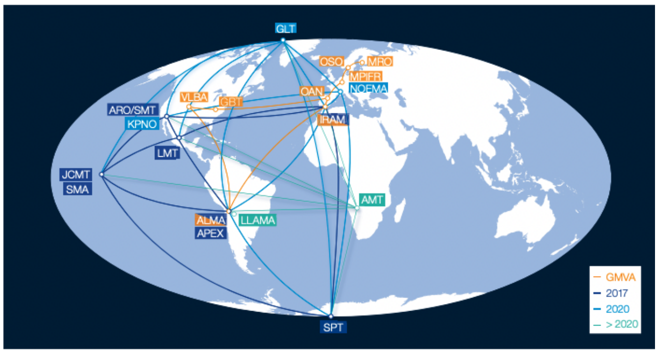


Figure 2: The EHT Network (from [17]). The 2017 network is shown in blue, with two new telescopes being added in 2020. The AMT will be added in 2024.

3 Imaging the event horizons of the SMBHs in Messier 87 and our Milky Way galaxy

In an observing campaign in April 2017, the SMBH at the centre of Messier 87 was imaged using the EHT. The images were released in April 2019[22]. Although M87 is $\sim$ 2000 farther away than our Galactic centre[17], it hosts a SMBH with a mass of $\sim$ 16 billion$M_\odot$[23]. Therefore, the angular diameter of its SMBH is only slightly smaller than for our Galaxy. Figure 3 shows the first-ever images of the shadow of a supermassive black hole.

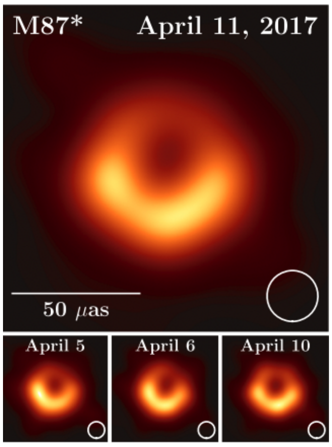


Figure 3: The shadow of the event horizon of M87 [22]

During the same observing campaign, the EHT also observed Sagittarius A*, and the first images of our own Galaxy's SHMB (Figure 4) were released in May 2022[24].

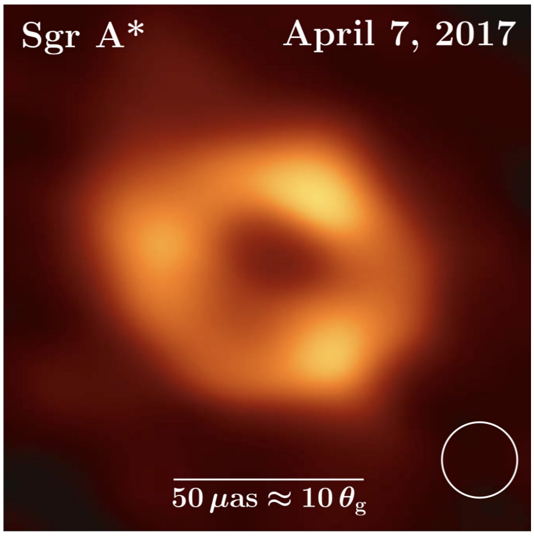


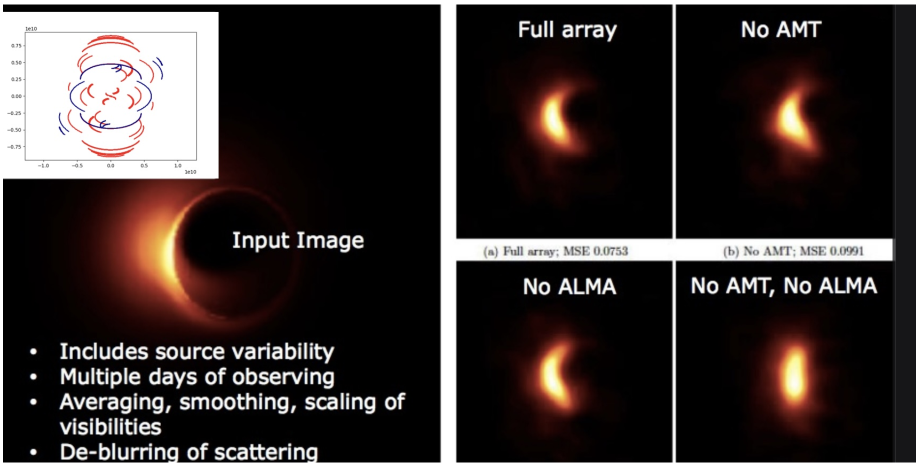
Figure 4: The shadow of the event horizon of Sagittarius A* [24]

4 The Africa Millimetre Telescope

Although the EHT has successfully produced images of the shadow of the SMBHs in both M87 and Sagittarius A*, simulations show that the resolution of the array will be greatly enhanced by the addition of a millimetre-wave dish on the African continent, specifically, on Mount Gamsberg in Namibia. Figure 5 shows simulations of the appearance of an input synthetic image with and without both ALMA and the AMT. Figure 6 shows where in Namibia Mount Gamsberg is located, it is approximately 150 km east-south-east of Windhoek, in one of the driest parts of the country. Figure 7 shows the mountain, with the current access road to the summit.

As can be seen from Figure 5, the improvement in resolution by adding the AMT is actually greater than the inclusion of ALMA. This is because the AMT briefly allows for the maximum possible baseline between its location in Namibia and the elements of the EHT which are in Hawaii, a full earth-diameter away.

Site testing of this site conducted by the European Southern Observatory (ESO) from mid-1994 to mid-1995[25] showed that Mount Gamsberg, at an elevation of 2400m, has low precipitable water vapour, particularly during the dry season from May to October (see Figure 8). This makes it ideal for millimetre-wave astronomy.



- Includes source variability
- Multiple days of observing
- Averaging, smoothing, scaling of visibilities
- De-blurring of scattering

Figure 5: Simulated images and with and without the AMT

Figure 6: The location of Mount Gamsberg

Figure 7: Mount Gamsberg, with the access road to the summit in the foreground.

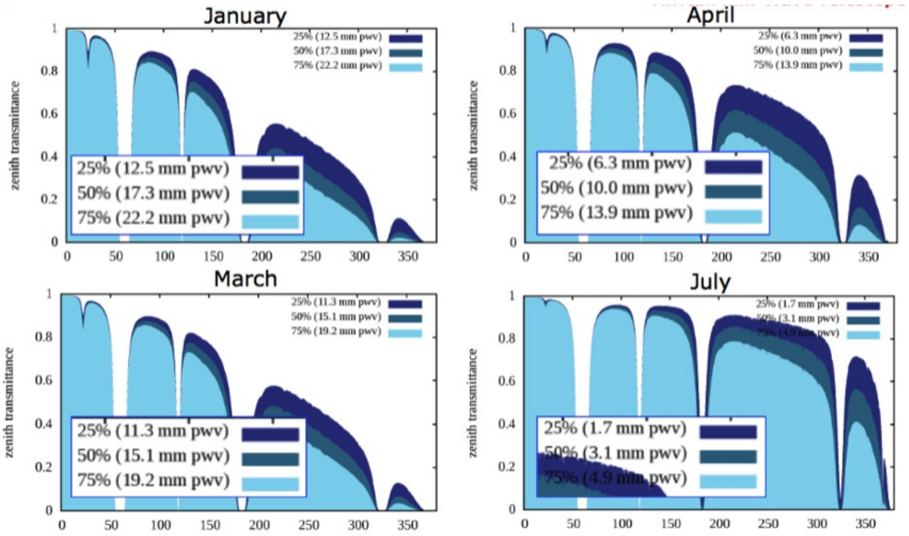


Figure 8: Precipitable water vapour at Mount Gamsberg as measured by ESO from mid-1994 to mid-1995 using a radiometer[25].

5 The Telescope

To reduce costs, the AMT project will use the decommissioned 15-metre Swedish-ESO Sub-millimetre Telescope (SEST). SEST was operated at La Silla in Chile from 1987 to 2003, when it was decommissioned[26],[27]. SEST will be dismantled, and initially shipped to France for repair and refurbishment. Then, it will be shipped to Namibia, where it will be transported in sections to the summit of Mount Gamsberg. The largest sections of the telescope are the gears, which are a few metres in size and weigh about 5 metric tonnes. In order for such large items to be transported to the summit, the access road shown in Figure 7 will need to be improved. Power at the summit will be provided by solar power with large storage batteries, and data communication will use the current communication mast on the mountain, with an upgrade for high data-rate transfers.

Figure 9: The Swedish ESO Sub-millimetre Telescope (SEST) at La Silla, Chile. This telescope operated between 1987 and 2003, when it was decommissioned[26],[27].

6 Summary and Conclusions

In the last few years we have entered a new era in millimetre-wave astronomy, obtaining images for the first time of the shadows of the supermassive black holes at the centres of Messier 87 and our own Milky Way. This has been achieved by linking together millimetre-wave telescopes on several continents and using the technique of very long baseline interferometry to produce resolutions of a few tens of a micro-arcsecond. Simulations show that the resolution of the network of telescopes will be greatly improved by the addition of a telescope in Africa, and Mount Gambserg in Namibia has been chosen as the most suitable site. The Africa Millimetre Telescope will use the decommissioned 15-metre Swedish-ESO Submillimetre Telescope, and will see first light in April 2024.

References

[1] E.E. Salpeter. Accretion of interstellar matter by massive objects. *Astrophysical Journal*, 140:796–800, 1964.

[2] D. Lynden-Bell and M. Rees. On quasars, dust and the galactic centre. *Monthly Notices of the Royal Astronomical Society*, 152:461–475, 1971.

[3] M. Rees. Black holes. *The Observatory*, 94:168–179, 1974.

[4] L Ferrarese and D Merritt. A fundamental relation between supermassive black holes and their host galaxies. *Astrophysical Journal*, 539:L9–L12, 2000.

[5] K Gebhardt, Bender R, Bower G, and A Dressler etal. A relationship between nuclear black hole mass and galaxy velocity dispersion. *Astrophysical Journal*, 539:L13–L16, 2000.

[6] S Tremaine, K Gebhardt, and R Bender etal. A relationship between nuclear black hole mass and galaxy velocity dispersion. *Astrophysical Journal*, 574:740–753, 2002.

[7] A King. Black holes, galaxy formation, and the $m_{BH} - \sigma$ relation. *Astrophysical Journal*, 596:L27—L29, 2003.

[8] B. Balick and R.L. Brown. Intense sub-arcsecond structure in the galactic center. *Astrophysical Journal*, 194:265–270, 1974.

[9] R Genzel, N Thatte, A Krabbe, H Kroker, and L E Tacconi-Garman. The dark mass concentration in the central parsec of the milky way. *Astrophysical Journal*, 472:153–172, 1996.

[10] A Eckart and R Genzel. Stellar proper motions in the central 0.1 pc of the galaxy. *Monthly Notices of the Royal Astronomical Society*, 284:576–598, 1997.

[11] A M Ghez, B L Klein, M Morris, and E E Becklin. High proper-motion stars in the vicinity of satittarius a*: Evidence for a supermassive black hole at the center of our galaxy. *Astrophysical Journal*, 509:678–686, 1998.

[12] J R Lu, A M Ghez, S D Hornstein, M R Morris, E E Becklin, and K Matthews. A disk of young stars at the galactic center as determined by individual stellar orbits. *Astrophysical Journal*, 690(1463–1487), 2009.

[13] S. Gillessen, F. Eisenhauer, S. Trippe, T. Alexander, R. Genzel, F. Martins, and T. Ott. Monitoring stellar orbits around the massive black hole in the galactic center. *Astrophysical Journal*, 692:1075–1109, 2009.

[14] A.M. Ghez, S. Salim, N.N. Weinberg, J.R. Lu, T. Do, J.K. Dunn, K. Matthews, M.R. Morris, S. Yelda, E.E. Becklin, T. Kremenek, M. Milosavljevic, and Naiman. J. Measuring distance and properties of the milky way's central supermassive black hole with stellar orbits. *Astronomy and Astrophysics*, 689:1044–1062, 2008.

[15] R Genzel and A M Ghez. The nobel prize in physics, 2020, "for the discovery of a supermassive compact object at the centre of our galaxy", https://www.nobelprize.org/prizes/physics/2020/summary/, 2020.

[16] K Schwarzschild. Über das gravitationsfeld eines massenpuktes nach der einsteinschen theorie (on the gravitational field of a mass point according to einstein's theory). *Sitzungsberichte der Deutschen Akademie der Wissenschaften zu Berlin, Klasse fur Mathematik, Physik, und Technik*, page 189, 1916.

[17] C. Goddi, G. Crew, and V. etal. Impellizzeri. First m87 event horizon telescope results and the role of alma. *Messenger*, 177:25–35, 2019.

[18] J M Bardeen. Rapidly rotating stars, disks, and black holes. In C DeWitt and B S DeWitt, editors, *Black Holes*, pages 241–289. Summer School of Theoretical Physics of the University of Grenoble at Les Houches, Gordon and Breach, NY, 1973.

[19] J Falcke, F Melia, and E Agol. The shadow of the black hole at the galactic center. In *Cosmic Explosions*, volume 522, pages 317–320. American Insitute of Physics, 2000.

[20] R Abuter, A Amorim, and M Bauböck etal. A geometric distance measurement to the galactic center black hole with 0.3 *Astronomy and Astrophysics*, 625:L10, 2019.

[21] S Doelman, E Agol, and D Backer etal. Imaging an event horizon: submm-vlbi of a super massive black hole. In *Astronomy Decadal Review*, 2009.

[22] The Event Horizon Telescope Collaboration. First m87 event horizon telescope results. i. the shadow of the supermassive black hole. *Astrophysical Journal*, 875(L1), 2019.

[23] Jonelle L Walsh, A J Barth, L C Ho, and M Sarzi. The m87 black hole mass from gas-dynamical models of space telescope imaging spectrograph observations. *Astrophysical Journal*, 770:86–96, 2013.

[24] The Event Horizon Collaboration. First Sagittarius A* event horizon telescope results. i. the shadow of the supermassive black hole at the center of the milky way. *Astrophysical Journal*, 930:L12–32, 2022.

[25] S Sarazin. Environmental conditions on potential observatories - gambserg (namibia) for the months july 1994 to july 1995, 1995.

[26] R S Booth, M J de Jong, and P A Shaver. The swedish-eso submillimetre telescope. *Messenger*, 48:2–6, 1987.

[27] C Madsen. Swedish-eso 15m submillimeter telescope (sest), 2003.