A Black Hole Finally (Un)Seen in the Centre of a Galaxy*

The Sharpest Image Ever

Rajaram Nityananda

The uneven ring of radio emission at the centre of the distant galaxy, M87, has excited astronomers, physicists, and the general public, as the first view of a black hole. Everything about the project, known as the EHT – Event Horizon Telescope – is extreme. The observation combines signals from radio telescopes distributed over an entire hemisphere, operating at millimetre wavelengths on high mountains and at the Earth's poles. These telescopes are synchronised by the best atomic clocks, and massive amounts of data recording and number crunching were needed. To interpret the results, elaborate models of the energy source, based on Einstein's general theory of relativity (GTR) were constructed. The team had over three hundred scientists from more than a hundred institutions, some of whom worked for nearly a decade towards this goal.

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1. Early Speculations About Dark Astronomical Objects

This image on the front cover of this issue (also see *Figure* 1) did not spring overnight out of the blue. It is a major milestone in a long journey which involved repeated exchanges between physics, astronomy, and technology. The story begins as long ago as 1783 when John Michell, an English clergyman, dared to think of a body from which light could not escape. He also suggested how such a body might be detected by observing its effects on the surrounding bodies. An early premonition of what we now

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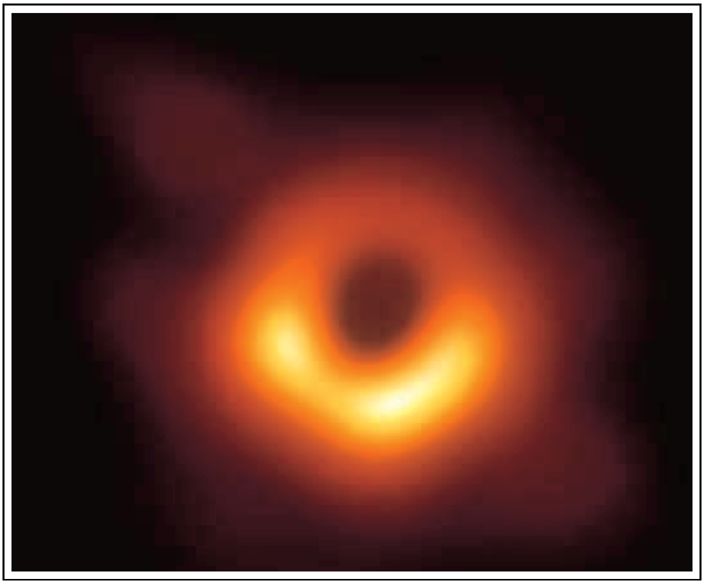

Figure 1. Image of the ring around the M87 black hole produced by the EHT. Source: *Wikimedia Commons*. The image was originally published in First M87 Event Horizon Telescope Results. IV. Imaging the Central Supermassive Black Hole, The Event Horizon Telescope Collaboration *et.al.*, *The Astrophysical Journal Letters*, 875:L4 (52pp), April 2019. Published by: The American Astronomical Society

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call a black hole is also credited to the famous French scientist Pierre-Simon Laplace, who is regarded as Newton's successor in celestial mechanics – the science of planetary motion. His independent speculation was published in 1799. Both Michell and Laplace imagined a body as dense as the Sun but five hundred times larger in size and hence 125 million (500^3) times heavier than the Sun. Their calculations (see *Box* 1) showed that such an object should be able to trap light.

In 1781, the French astronomer Charles Messier published a catalogue of fuzzy-looking objects which were fixed in the sky but definitely not stars. The ring image on the cover of this issue is located at the centre of object number 87 in his list.

We thus have a minimum radius below which the escape speed from a body of a given mass exceeds the speed of light. This radius is proportional to the mass. For 6 billion times the mass of the Sun, the value estimated for the M87 black hole, the radius would be 18 billion kilometres, This is the distance travelled by light in 60 000 seconds – little less that one light-day.

2. Messier's Catalogue of Nebulae

Meanwhile, in 1781, the French astronomer Charles Messier published a catalogue of more than a hundred fuzzy-looking objects

Box 1. The Michell–Laplace Estimate

The Michell–Laplace estimate is based on the familiar concept of escape velocity, which can be expressed either in terms of the mass and radius of the body, or (as they did) in terms of density and radius:

$$\begin{aligned} V^2_{\text{escape}} &= 2\mathrm{G}M/R = 8\pi \mathrm{G}\rho R^2/3, \\ R &= 2\mathrm{G}M/v^2_{\text{escape}}, \\ \text{Put escape velocity} &= c, \\ R_{\min} \equiv R_{\text{Schwarzchild}} &= \frac{2\mathrm{G}M}{c^2}. \end{aligned}$$

We have inserted the name of Karl Schwarzschild, the German astronomer, as a subscript to this minimum radius. His exact formula for the radius of a black hole agrees with the guess made by Michell and Laplace! For a black hole as massive as the Sun, putting in the values of G, M, R

$$R_\mathrm{S} \approx 3\,\mathrm{km}.$$

which were fixed in the sky but definitely not stars. The ring image on the cover of this issue is located at the centre of object number 87 in his list. Messier's catalogue was simply meant to be a list of objects for his fellow comet hunters to ignore – since they kept their telescopes trained to look for *moving* fuzzy objects which could then be named after them. The objects whose positions in the sky were fixed, were called 'nebulae' because of the apparent resemblance to clouds.

3. Enter Einstein

The study of planetary movements in the solar system pioneered by Laplace moved from triumph to triumph in the nineteenth century. The only discrepancy was the planet Mercury. The major axis of its elliptical orbit was turning slowly in excess of predictions from Newton's law – the excess was one revolution in thirty thousand years. But Einstein was unhappy with Newton's theory for a different reason – the theory requires instantaneous action

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at a distance. Special relativity does not allow any influence to travel faster than light and certainly not instantaneously. In fact, the notion of simultaneity has no absolute meaning in this theory. It took Einstein ten years to fix this problem. He proposed a theory of gravitation, which he called the general theory of relativity (GTR). In this theory, he banished gravitational force and replaced it by curved geometry of space and time[1].

[1]See S Chaturvedi, R Simon and N Mukunda, Space, Time, and Relativity, *Resonance*, Vol.11, No.7, 2006.

In 1915, Einstein was only able to find the approximate solutions of his ten complicated equations, which explained the orbit of Mercury. He also predicted the bending of light as it passes a massive object, and the reddening of light as it moves away from a massive body. We should not, however, attribute the first theoretical glimpse of black holes to Einstein. That honour goes to the astronomer Karl Schwarzschild, who was serving in the German army in the First World War when Einstein's paper came out. Schwarzschild quickly found the first exact mathematical solution of Einstein's equations. (Contrary to popular opinion, Einstein was not an expert mathematician!) This solution describes the gravitational field outside a spherically symmetric distribution of matter. Tragically, Schwarzschild barely lived long enough to see his work in print in 1916.

4. The Long Gestation of the Black Hole Idea

Our current understanding is that Schwarzschild's solution describes a black hole. This is a sphere from which even light cannot escape and within which any matter falls inexorably to a still ill-understood fate. This sphere beyond which we cannot see is called the 'event horizon'.

The physical meaning of Schwarzschild's mathematics remained unclear for decades. In Einstein's theory, the same physical object can take many different mathematical guises, not all of which are equally easy to interpret. Our current understanding is that Schwarzschild's solution when properly extended and interpreted, describes a black hole. This is a sphere from which even light cannot escape and within which any matter falls inexorably to a still ill-understood fate. The sphere into which we cannot see is called the 'event horizon' and gives the EHT its name. This modern understanding of the black hole had to wait till a 1958 paper by David Finkelstein, whose name should be better known than it is. Jakob Bekenstein, as a PhD student in 1973, opened the gates for

Hawking to prove that black holes are not really black but emit radiation. It may be noted that 'Hawking radiation' is a quantum process and is negligible for astronomical black holes of the kind we are concerned with. To the mathematically equipped and inclined, brilliant work by Roger Penrose and Stephen Hawking in the mid-1960s added further strong evidence. They showed very generally that Einstein's equations can lead to 'singularities'. The big bang birth of our universe and the still ill-understood end of matter entering the event horizon are two examples.

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5. M87: A Strange Galaxy

When Galileo looked at the Milky Way with his telescope, he saw individual stars, and it was soon recognised that we live in a galaxy. We now know that it is a collection of one hundred billion stars. It took nearly three hundred years for astronomers to realise that many of the objects in Messier's catalogue were also galaxies made up of stars. One of the early defenders of this view was the American astronomer Heber Curtis, who was finally proved right when Edwin Hubble was able to see individual stars in our neighbour, the Andromeda galaxy.

In 1918, Curtis saw a strange line on one side of the centre of the galaxy M87 in his photographs. Although it was later named 'jet', suggesting some outflow of material and energy from the centre, its nature remained a mystery for 50 years (*Figure* 2).

First Radio Signals From M87: The next clue to the M87 mystery came from an unexpected direction. Many Australian, British, and US scientists were pressed into service to work on radar technology during the Second World War. Once released, they pioneered a new area – radio astronomy. In 1948, Sydney based scientists, John Bolton and Gordon Stanley, found a strong source of radio waves in the constellation of Virgo. They could only measure the position to a fraction of a degree, but boldly proposed, that the source might be identified with Messier 87 (M87), even though the galaxy was thought to be about thirty million light-years away (the modern value is 55 million).

Figure 2. M87 jet: A modern image taken with the Hubble space telescope. Source: *Wikimedia Commons*

Interferometry is a technique in which the signals from two radio telescopes are combined to measure the difference in arrival times. From this, one can then infer the direction and strength of the source. For waves, this difference is measured by comparing the arrival of crests and troughs at the two telescopes.

The technique they used is called interferometry – the signals from two radio telescopes are combined to measure the difference in arrival times. From this, one can then infer the direction and strength of the source. For waves, this difference is measured by comparing the arrival of crests and troughs at the two telescopes. (A similar effect plays a role in how we and most animals determine the direction of sound waves using two ears and appropriate hardware/software in the brain). Cleverly, they used just one telescope mounted on a cliff in New Zealand. The second was provided gratis by its image reflected in the sea, which is a good mirror for long radio waves. Leaving out this last twist, the same principle – of receiving and comparing signals at separated telescopes – underlies most of the radio astronomy today and lies at the foundation of the EHT effort (*Figure* 3). Clearly, for more than one source, or a complex source like a ring, one needs data from many telescopes to obtain the full image. Clearly, using a shorter wavelength and using a longer separation between the telescopes allows us to make an image with detail on a finer angular scale. This 'resolving power' is given by λ/D . For more details of this technique, see the article by Jayaram Chengalur, in *Resonance*[2].

[2]Jayaram N Chengalur, Radio Astronomy and the Giant Metre-Wave Radio Telescope, *Resonance*, Vol23, No.2, pp.165–182, 2018.

6. Black Holes Gain Respectability, Enter Astrophysics

Many questions regarding black holes were still being answered in the 1960s. It is not enough to produce one solution of Einstein's equations; one has to make sure it is stable. An unstable configuration, such as a pencil balancing on its point, is very short lived. It is not suitable as a model for an astronomical phenomenon. This issue of stability was settled definitively, at least for small disturbances of a Schwarzschild black hole, by C V Vishveshwara in his 1970 PhD thesis at the University of Maryland. (C, does not stand for a first name but for Channapatna, his home town sixty kilometres southwest of Bengaluru, India.). This pioneering calculation corrected the earlier work which did not properly account for the true nature of the event horizon.

Stability implies that the formation of a black hole is accompanied by damped oscillations. These were detected by the LIGO Observatory in 2016[3] when it detected the gravitational waves from two merging black holes. The observed signal from this event closely matches the theory and the result of elaborate computations based on Einstein's equations for gravity. Theory, computation, and observation have now cleared reasonable doubts about our overall picture of black holes. This is true not just for the Schwarzschild black hole but generalisation to rotating black holes. This was found by Roy Kerr of New Zealand. The long time interval from 1916 to 1963 is a good indicator of the mathematical and conceptual challenges of working with Einstein's theory. Most astronomical objects rotate, and black holes are no exception. Today, Kerr's solution to Einstein's equations is part of the toolkit of every practising and aspiring black hole astrophysicist.

[3]See *Resonance*, Vol.21, No.3, 2016.

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– contained enormous energy sources in a very small volume. Some of them were measured to emit a trillion (10^{12}) times the energy output of the Sun, just in the form of radio waves! Edwin Salpeter in the US and Yakov Zeldovich in Russia, two pioneers of theoretical astrophysics, independently invoked black holes as the 'central engines' of these galaxies as early as 1964. It took another decade for this insight to be generally accepted. Interestingly, when astronomers see an outflow of energy and matter or an explosion, they often invoke the opposite process of implosion – fall under gravity. The reason is that a falling body picks up speed, and this energy can be converted to other forms such as radiation or an outflowing jet. The combination of rotation and electrical conduction produces magnetic fields – a kind of dynamo. Any small magnetic field traversed by a moving conductor produces currents, which in turn produce more magnetic field. This process is believed to operate in a disc of hot, ionised gas rotating around and gradually falling towards the black hole. The energy needed to build up this field comes from the potential energy of the material as it moves to lower, smaller radius orbits because of friction. This is somewhat similar to the way artificial Earth satellites spiral in under atmospheric drag (fortunately, most of them burn up before they reach the Earth). This process can be understood using Newtonian gravity. But one process is peculiar to rotating black holes. As magnetic fields penetrate the event horizon, that surface too acts as a moving conductor, generating high voltages which in turn power jets by tapping the energy of rotation.

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Over the years, elaborate computer models with all these ingredients have been created and tuned to match the observations of these 'active galaxies' like M87. The increasing success of these models suggested that one should now look for the central black hole directly, by radio interferometry. Heino Falcke in Germany and his colleagues analysed this possibility and showed that this goal was difficult but within reach. Sheperd Doeleman observed the centres of galaxies at the smallest angular scale then feasible, for his PhD thesis at MIT in the US. These two scientists

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were just born around the time Hawking and Penrose were trying to put black holes on a firm theoretical footing! They joined forces and are now two of the leaders of the EHT effort. This involved finding funding, getting co-operation and participation from many observatories in different countries, which had been build for a completely different purpose. In that way, this effort was different from the LIGO collaboration which was created from the start for a single goal.

The technological progress and scale needed for the EHT to work is evident from some numbers. In 1948, the telescopes (actually one telescope and its image in the sea!) were separated by 600 metres and operated at a wavelength of 2 metres. The 'pictures' were blurred by λ/D = 1/300 in radians[4] or roughly one-fifth of a degree. Even human eyes do ten times better. By the 1990s, enough was known about the hypothetical black hole in M87 to estimate the angle subtended at Earth. This is one part in a hundred million – 10^{-8} – of a degree. Clearly, the separation D had to increase, and the wavelength λ had to decrease, to achieve this level of detail in the radio image. In 2017, when the EHT took the data used to make create the first image of the black hole, the telescopes were separated by 10,000 kilometres, at a wavelength of 1.3 millimetres (*Figure* 3). The formula for the angular resolution shows that it is now just enough to see details on the scale of the event horizon.

[4]For more on the resolving power of telescopes, see *Resonance*, Measuring the sizes of stars: Fringe benefits of Interferometry, Vol.122, No.7, 645–657, 2017.

Why did it take two years to produce the image? The radio signals – and the time accurate to nanoseconds – was separately recorded at each telescope. There was no question of sending the data by the usual methods. There are no optical fibres at the South Pole and in any case, the data rate was as large as 32 gigabits per second. The radio signals, therefore, had to be recorded on hard disks which were then shipped to two locations, one in Germany and one in the US. The highly computer-intensive comparison of the different signals followed by preparation of the image then began. Many cross-checks are needed to make such a major claim. In fact, crucial steps were carried out by separate sub-teams independently, and only after they agreed, were the results finalised.

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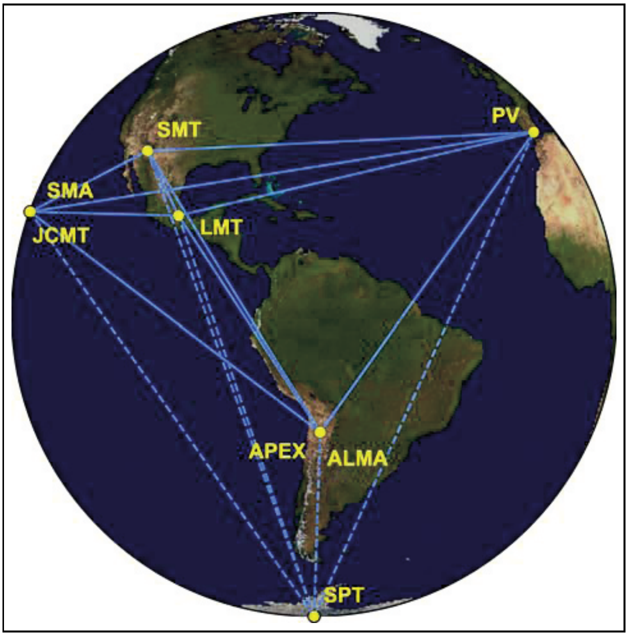

Figure 3. A view of the telescopes used for making the image (Courtesy: EHT Collaboration. The figure was originally published by The Event Horizon Telescope Collaboration *et.al.*, in First M87 Event Horizon Telescope Results. I. The Shadow of the Supermassive Black Hole, *The Astrophysical Journal Letters*, Vol.875, No.1, L1(17pp), April 2019.)

All this happened over two years, while the rest of the astronomical community waited.

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Is the image what is to be expected? The team includes people who have worked for years on computing the properties of a disc of matter surrounding the proposed black hole in M87 and similar galaxies. The modelling includes the outflowing jet and calculates the radio emission which is mainly from electrons going round in magnetic fields. The radiation does not come straight to us because it is deflected by the gravity of the spinning black hole. In fact, some of the radiation arrives at Earth after circling the black hole more than once! What we thus see is a highly distorted version of what is present at the source. All this was accounted for in the modelling and presented in six detailed papers which came out simultaneously with the press release in early April 2019. What is most important is that we do not see any radiation coming straight from the black hole – that is not allowed by general relativity. In that darkness lies the long-sought proof of the central black hole – hence the "unseen" in the title of this piece.

One of the telescopes in the collaboration is on the peak of Mauna Kea in Hawaii. Thanks to its altitude and clear skies, a veritable forest of radio and optical observatories have sprung up. The original inhabitants had to surrender the land which they regarded as sacred and indeed have fought against a major proposed international project for a 30-metre optical telescope – successfully so far! Perhaps as a concession to local sentiment, the EHT team has proposed the name *Powehi* for this object. It translates to something like "the endless dark source of creation" in one of the local myths. After this groundbreaking work, and the LIGO detections, black holes have now moved decisively from widely held, useful and even compelling myth to observed reality. The future will see even more routine use of black holes in understanding astronomical observations. As the old adage from particle physics states, "Yesterday's discovery is today's calibration and tomorrow's background."

Suggested Reading

[1] **For more detailed information about black holes, a good source is https://en.wikipedia.org/wiki/Black_hole**

[2] **For more on active galaxies of different kinds, see https://en.wikipedia.org/wiki/Active_galactic_nucleus**

[3] **A brief introduction to radio astronomy can be found in the article https://en.wikipedia.org/wiki/Radio_astronomy**

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