SEEING THE INVISIBLE: IMAGING A BLACK HOLE

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In early April this year, newspapers and online websites were agog with the news that astronomers had obtained the first image of a black hole known to reside in a distant galaxy called M87. Why did this image cause such a stir?

In April 2019, astronomers managed to obtain an image of a black hole for the first time (see **Fig. 1**). This black hole is known to reside in the heart of a distant galaxy called M87 (see **Box 1**).

Based on measurements of the velocities of rapidly moving stars and gas near the centre of M87, the mass of this black hole is estimated to be billions of times more than that of our sun. Similarly, the size of this black hole is calculated to be billions of kilometres — bigger than our solar system (see **Box 2**). However, because of its distance from us, the angular size of the expected image of the black hole itself is very small, one part in hundred million (10^{-8}) of a degree. Despite this, astronomers chose to image it because this is the largest angle subtended by a black hole known to us.

The idea of a black hole

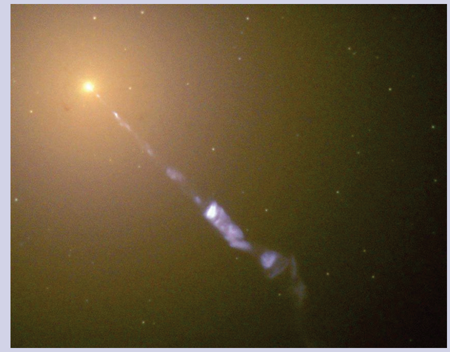
Our story begins more than 200 years ago. In 1783, John Michell, an English clergyman imagined a body from which even light could not escape. Another early proposal of what we now call a black hole came from the writings of the French

Box 1. M87:

The galaxy M87, an abbreviation of Messier 87, gets its name from its position (the 87^{th}) in an astronomical catalogue (The catalog of nebulae and star clusters), first published in 1771 by the French astronomer Charles Messier. The catalogue listed 110 nebulae and star clusters, that have since come to be known as the **Messier objects**.

When Galileo looked at the Milky Way with his telescope, he saw individual stars. It was gradually recognized that we live in a galaxy — a collection of around one hundred billion stars. It then took nearly 300 years for astronomers to realize that many of the diffuse objects were galaxies outside our own, and were also 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 photographed an unusual sharp line like object, apparently coming out on one side of the centre of the galaxy M87. Although it was later given the name of 'jet', suggesting some outflow of material and energy from the centre, its nature remained a mystery for 50 years.



M87 jet: a modern image taken with the Hubble space telescope.

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Fig. 1. The image of a 'black hole' at the heart of galaxy M87. This image was made by combining radio waves received from dishes (antennas) distributed over the entire globe.

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scientist Pierre-Simon Laplace in 1799. Both Michell and Laplace based their calculations on the idea of escape velocity (see **Box 3**).

A more comprehensive understanding of black holes came in 1915 from Einstein's general theory of relativity (abbreviated to GTR) based on the curved geometry of space and time. Because its mathematics was so unfamiliar, it took the physics and astronomy community nearly four decades to agree that this theory could be used to describe a black hole. GTR describes the spherical surface of a black hole as a wave of light that is unable to travel outwards because of gravity.

Box 2. Giant black holes:

The existence of black holes of this size was first suspected in the mid-20^{th} century. After many unsuccessful attempts to explain the energetic radio waves and other forms of electromagnetic radiations that the earth received from distant galaxies like M87, a mechanism for this energy output was generally accepted. The primary source of these radiations is now believed to be a disc of hot gas with a strong magnetic field, which is in orbit around a 'giant' black hole at the centre of each of these galaxies.

Does this contradict Einstein's special theory of relativity, proposed in 1905, which suggests that all observers will see light travelling at the same speed (c = 300,000 km/s)? This apparent contradiction can be resolved since the spherical wavefront that represents the

Box 3. Escape velocity and the idea of black holes:

This is the minimum speed required by a body to escape the gravitational field of a massive object so that it does not fall back. Newton's theory of gravity shows that the square of the escape velocity is proportional to the mass, and inversely proportional to the radius of the body. If we consider a body with a mass M, a radius R, and with an escape velocity equal to the speed of light (c):

$$R = (2\ G\ M) / c^2$$

Here, G is the constant in Newton's law of gravitation, which expresses the force between two masses in terms of the distance between them. Or,

$$F = (G\ M_1 M_2) / R^2$$

If we substitute the values for G, the speed of light, and the mass of the sun, we find that R has a value of just 3 km. This means that if the entire mass of the sun was packed into a sphere with a 3 km radius, it would become capable of trapping light. Since the actual radius of our sun is about 700,000 kilometres, there is no danger of it trapping its own light in its present state!

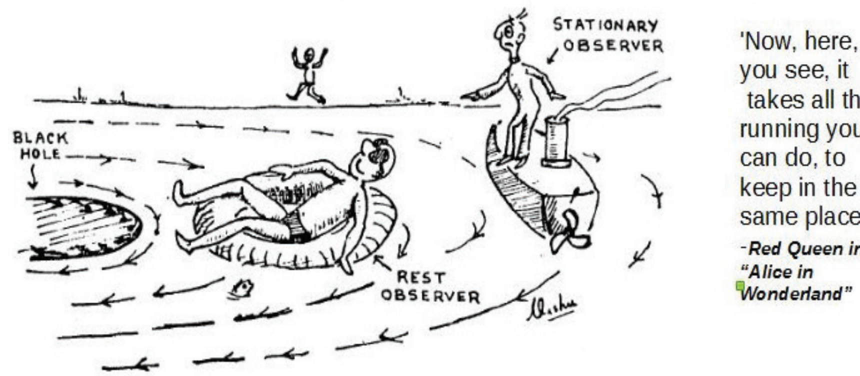


Fig. 2. C. V. Vishweshwara's cartoon illustrating the behaviour of observers around a rotating black hole, and drawing a parallel with 'Alice in Wonderland'.

Credits: This image is derived from C. V. Vishweshwara's article "Black Holes for Bedtime" in the volume "Gravitation, Quanta and the Universe; proceedings of the Einstein Centenary Symposium held on 29^{th} January–3^{rd} February, 1979, in Ahmedabad, India." Edited by A. R. Prasanna, J. V. Narlikar, and C. V. Vishveshwara. A Halsted Press Book, published by John Wiley & Sons, New York, 1980, p154-167. Image reproduced here courtesy Prof. Sarawathi Visweshwara.

surface of the black hole only appears to be standing still when viewed from far away (see **Box 4**). An observer who is present at this surface will see it moving outwards at the speed of light, because she cannot stand still – she is falling in! This wavefront is called an **Event Horizon.** If an event occurs inside this surface, no light or message from it is sent to the outside world. To an observer standing outside, this surface is like a horizon – we don't see beyond it. It is for this reason that the network of researchers who worked on making the image of the black hole called their collaboration the **Event Horizon Telescope** (or, EHT).

Today, astronomers believe that a black hole is the final state of a massive star (one that is more than 20 times heavier than our sun). According to this view, after a massive star exhausts its source of energy, it collapses to a much smaller size. Its large mass and small radius mean that the force of gravity on its surface is so strong that nothing, not even light, is able to escape it. These predictions were validated in 2016, when the LIGO observatories 'heard' ripples of two black holes that were each 30 times heavier than our sun.

Black holes at the heart of galaxies like M87 are known to rotate. This is because a black hole is formed by collecting material, like gas or even whole stars, that orbited it before falling into it. To understand this, think of the black hole pulling in space and time like a waterfall pulls in floating objects. If we think of spacetime around a rotating black hole as a fluid, it is not only being pulled in, but also being swirled around. A particle, or even a ray of light, coming inwards moves sideways in the direction of rotation. This idea is aptly illustrated in a cartoon by C. V. Vishveshwara, a very well-known researcher in the area of GTR who also played a major role in setting up the Bengaluru planetarium (see **Fig. 2**).

Radio waves from M87

Many Australian, British, and US scientists who worked on radar technology during the World War II turned their attention to the study of radio waves from astronomical objects in the post-war period. This was far more challenging than using visible light to probe the universe. The main disadvantage was the fact that the wavelength of radio waves (which is measured in centimeters or meters) was much longer than that of visible light (which is about half a micrometer). This meant that not only was it not possible to determine the precise position of the source of radio waves and its finer details, there was no clue as to how far away the source was.

Nevertheless, this approach was used to make many outstanding discoveries. For e.g., in 1948, two Sydney based scientists – John Bolton and Gordon Stanley – found a strong source of radio waves in the constellation of Virgo. They offered the tentative proposal that this source was the same galaxy known to us as M87 even though the object was thought to be about 30 million light-years away (the modern value is 55 million). The technique they used for this discovery is called **interferometry.** In this technique, radio waves arriving at two (or more) radio telescopes are compared to measure the difference in arrival times of the crests and the troughs. One can then infer the direction and strength of the source from these measurements. This is similar to how we, and most other animals, determine the direction of sound waves using two ears and the appropriate hardware/software in the brain. The same principle – of receiving and accurately comparing signals at telescopes separated in space – underlies most of radio astronomy today, and is the foundation of the EHT effort (see **Box 5**).

Around the beginning of this century, some of the bolder scientists realized that radio telescopes and the techniques of radio astronomy had reached a stage where viewing the surroundings of a black hole was just about possible. Since the technology (using millimeter waves) required to do this is quite demanding (see **Box 6**), the EHT project required the co-operation and collaboration of eight different telescopes (see **Fig. 3**). Many of these observatories are located

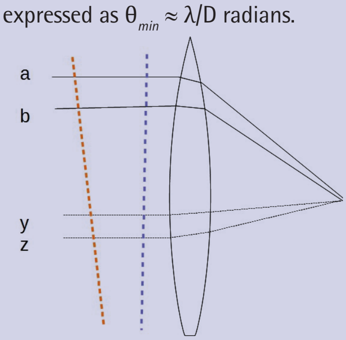
Box 4. Visualizing the wave front:

To give an analogy, the wavefront is like a person who is running upwards on a downward moving escalator at the same speed but in the opposite direction. Viewed from above, he is standing still, but viewed by someone on the escalator who is moving downwards, he is travelling outward!

Box 5. Interferometry:

Data from many radio telescopes is needed to obtain a complete image of more than one source, or a complex source like a ring. The 'resolving power' of such an array of radio telescopes is defined by the minimum angle θ_{min} between two sources of radio waves (or light, or any other form of electromagnetic radiation) which the instrument can distinguish as being separate. If the two sources are closer than this angle, then they appear as one blurred image in the picture made by this instrument.

The formula for θ_{min} is particularly simple if the angle is expressed in radians (remember: 1 radian = the angle subtended by an arc of unit length at the centre of a circle of unit radius = ~ 57.3 degrees). Since the arc and the chord are equal for much smaller angles, we can simply divide the size of an object by its distance to get the value of the angle. For e.g., an adult finger at arm's length (about 60 cm) and 2 cm width subtends 2/60=1/30 radians or about 2 degrees. Thus, the resolving power of a telescope of size D using a wavelength λ is expressed as $\theta_{min} \approx \lambda/D$ radians.



The image above shows the limits to resolution of an array of radio telescopes. The blue dashed line shows a plane wavefront, originating from a distant astronomical source of radiation. The associated rays are shown as lines perpendicular to the wavefront, and the lens focuses them to give the image corresponding to this source. The red dashed line is a wavefront coming from another source, separated by the angle θ_{min} in the sky in radians. This tilt leads to an extra path length of $D\theta_{min}$ between the rays reaching the top and the bottom of the lens. If this is much less than one wavelength, then the two sources cannot be seen as separate. This leads to the relation $\theta_{min} \approx \lambda/D$ radians.

at high altitudes since the water vapour in the lower atmosphere blocks these millimetre waves.

Significance of the ring shaped image of a black hole

Unlike laboratory physicists, astrophysicists do not control the systems they study. They have to work with radiation received on earth, and images which do not reveal the finer details of the object they are studying. Therefore, astrophysicists create 'models'. A model is a guess as to what kind of material, at what temperature, moving in what manner, will explain the limited observational information that astrophysicists have. Of course, any model has to obey the known laws of physics. Often,

Box 6. Using radio telescopes to view black holes:

The radius of the event horizon of the black hole in M87 was estimated to be about 50,000 light seconds. The distance to M87 was known to be 50 million light-years, or about 1.5 x 10^{15} light seconds. Therefore, the angle subtended at earth by the radius of the event horizon (θ_{min}) = ~3 x 10^{-11} radians. To achieve this angle, one would need a wavelength of approximately one third of a millimeter. Fortunately, matter surrounding the black hole emitting the radio waves is expected to be several times the event horizon radius. Therefore, a wavelength of 1.3 mm, which is available at many radio observatories, would suffice. These estimates assume a telescope separation of 10000 kilometres.

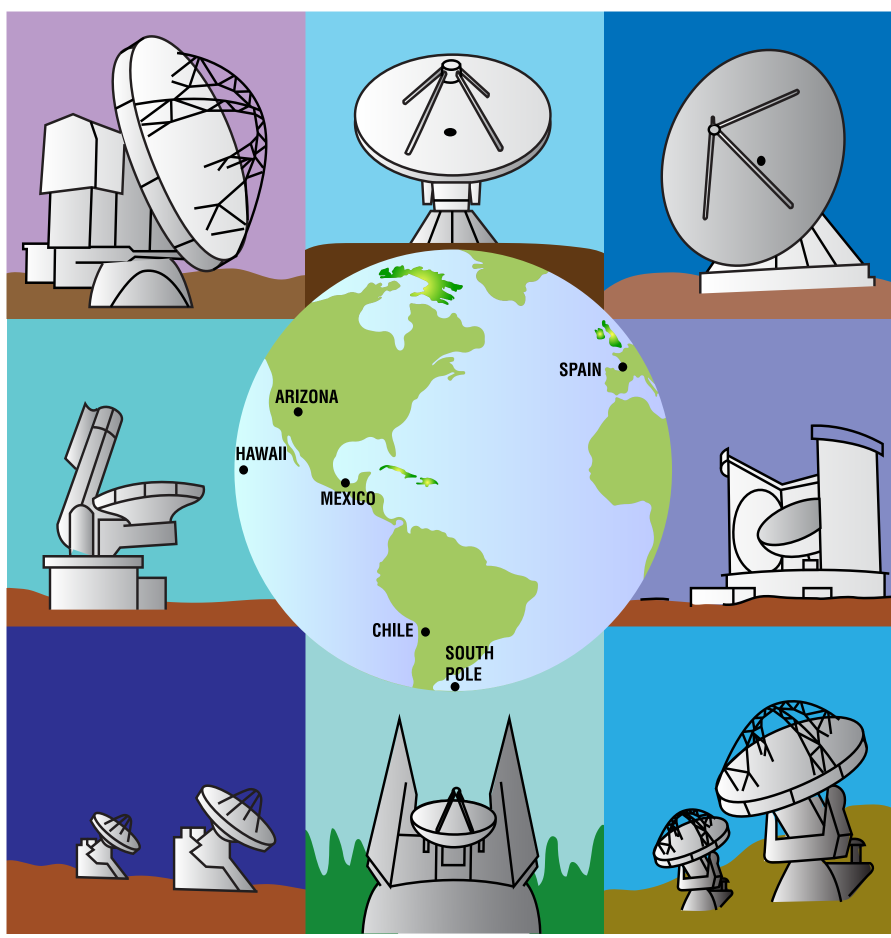


Fig. 3. The eight radio telescopes contributing to the EHT and their locations.

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very elaborate mathematics and/or computer programmes are needed to make predictions that can be compared with actual observations. When the observations are limited, many different models may work. With improvements in the quality of observations (for e.g., by observing an object at different wavelengths, or making images with higher resolving power), many of these models get rejected. If all goes well, the one model that survives is generally accepted as being the most plausible one.

It is this kind of process, over nearly half a century, that has given us a model that explains what is happening around the black hole to produce the powerful radio emissions we receive on earth. The black hole is surrounded by gas, which orbits it. The different gas streams at different radii and orbiting with different speeds results in friction. This has two consequences. One, the gas in the inner region spirals inwards into a lower orbit, in the same way that artificial satellites descend into lower orbits due to the friction of the earth's atmosphere. Two, this friction heats up the gas. Ultimately, the energy generated is accounted for by the potential energy lost while descending to lower orbits. As a very simple example, a stone falling towards the earth picks up kinetic energy, which becomes thermal energy when the stone hits the ground. At these high temperatures, the electrons in the gas ring get separated from the nuclei of the atoms, turning the gas into an electrical conductor. This carries electrical currents which produce a magnetic field. Electrons moving in curved orbits in a magnetic field emit radio waves. The rapidly rotating gas in the centre acts like a pump, and some of the gas is flung out and away from the black hole along the magnetic field lines. This too has a parallel — many borewells have a rapidly rotating 'centrifugal pump' at the bottom, which gives the water enough energy to climb to the surface.

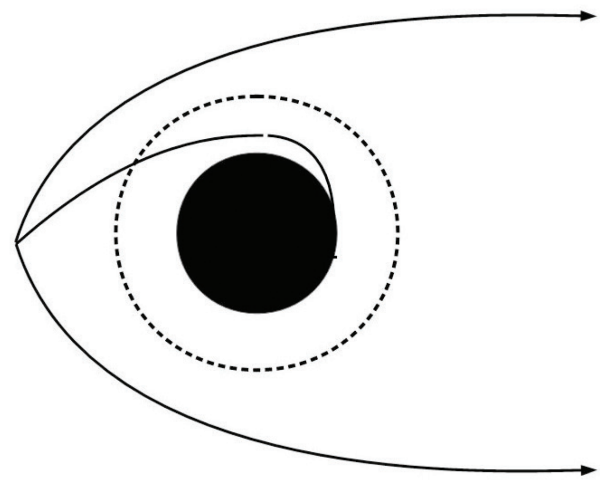


Fig. 4. Radiation originating near a nonrotating black hole. The dashed line is called the **photon sphere**. Any radiation crossing it falls into the event horizon. Rays that just miss it are bent and can reach a distant observer, forming a ring-shaped image. No rays are seen emanating from this sphere, which lies outside the event horizon.

While this model may seem very general, it was backed by large-scale computations to explain the energy and wavelength of the observed radiation even before the EHT work. The recent image allows astrophysicists to compare their model with actual observations to solve for some quantities which were unknown before. These include the mass of the black hole, how rapidly it is rotating, the amount of gas falling into it, and the strength of the magnetic field. Therefore, the recent image not only allows us to observe the black hole, but also learn more about its surroundings.

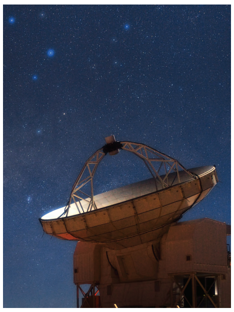
But, why is the central region of the image in darkness? The radiation coming from the orbiting gas is bent by the strong gravity of the black hole, creating the ring-like shape of the radio image. Rays which go too close to the black hole fall in (see **Fig. 4**). Since we do not receive them, this central region appears to be dark. This means that while the black hole continues to remain unseen and invisible, it produces a clear signature in the rays that just missed being captured by it.

To conclude

The excitement about the ring is justified. This image provides direct evidence for the existence of black holes — first offered as mere speculation more than two centuries ago. While it was worked out by astrophysicists in some detail even 50 years ago, the evidence was always indirect — calculations that were based on the assumption that a black hole seemed to agree with the observations. This was true both for the end states of massive stars and for the energy sources at the centre of galaxies. Clearly, astronomers were waiting for a more direct confirmation of the role of black holes. LIGO in 2016, and the EHT in 2019, have provided this long awaited evidence.

To a physicist, black holes are a fascinating aspect of gravitation, with properties like the event horizon, and the dragging of objects by a rotating black hole. Even more fascinating, but still unsolved, is the problem of what happens to matter once it crosses the event horizon. These recent astronomical discoveries will undoubtedly result in more work — both in terms of theory and observation. We can look forward to a better understanding of some of the most unusual objects in our universe.

Key takeaways



- In April 2019, astronomers managed to obtain an image of a black hole for the first time. This black hole resides in a distant galaxy called M87.
- The idea of a black hole as a body which traps even light is more than 200 years old. It received proper mathematical form in Einstein's theory of gravity.
- In 2016, the LIGO observatory found empirical evidence for the existence of black holes formed by the collapse of a star, after it has exhausted its source of energy, that was >20 times heavier than our sun.
- The image that was in the news this year was made by combining radio waves received from dishes (antennas) distributed over the entire globe, and the combined efforts of a large team of >300 authors (Event Horizon Telescope or EHT collaboration).
- This image provides conclusive evidence that the source of the energetic radio waves that the earth receives from the centre of M87 and similar galaxies is a disc of hot gas (carrying a strong magnetic field) that is orbiting a central black hole.

Note: Image used in the background of the article title – The Atacama Pathfinder Experiment (APEX) telescope at Chajnantor. Image credit: ESO/B. Tafreshi/TWAN (twanight.org), Wikimedia Commons. URL: https://commons.wikimedia.org/wiki/File:APEX_Stands_Sentry_on_Chajnantor.jpg. License: CC-BY.

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