Seeing is Believing*

First Image of a Supermassive Black Hole

Venkatessh Ramakrishnan

A black hole is an object with an extreme gravitational tug from which no light can escape. The nature of their strong gravity causes any material coming within the influence of its event horizon to be lost forever. The radiation from the hot disk of matter encircling the black hole opens the possibility to image these elusive objects, as it is impossible otherwise. Here, the first-ever image of the shadow of the supermassive black hole in a nearby galaxy, M87, is reported based on the observations by the Event Horizon Telescope.

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1. Historical Perspective of Black Holes

Of the many uncharted pits in the Universe, the one that fascinated the most by the theory of general relativity (GR) is the concept of a black hole. The notion of black holes was popularised by John Wheeler who attributed them to obscure objects with extreme gravitational potential. This idea immediately gained attention among theorists and observational scientists owing to their intense luminosity at every galaxy's centre (a misnomer since the black hole by itself does not emit any light).

This leads to the important question – the appearance of black holes. One of the first attempts to understand their appearance dates back to the early 1970s when the motion of a star in a tight orbit around a black hole was postulated (*Figure* 1). The important finding from these studies was the existence of 'photon orbit'. As the name suggests, photon orbit is the stable zone closest to the black hole where photons can orbit. Beneath this zone lies the

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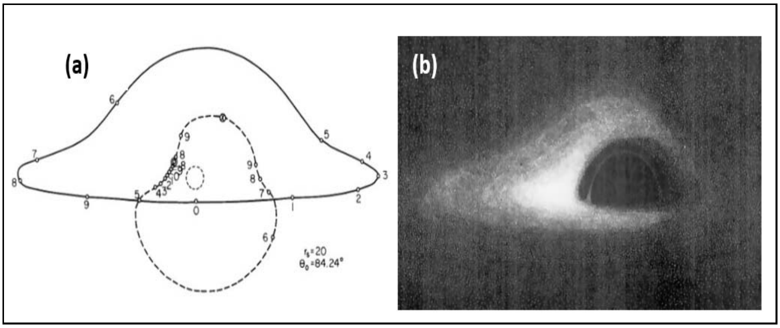

Figure 1. Black hole representations. **(a)** Orbit of a star around a black hole and **(b)** first-ever computer-generated image of a black hole. Credit: J P Luminet, Image of a spherical black hole with thin accretion disk, *Astronomy and Astrophysics*, Vol.75, No.1–2, pp.228–235.

event horizon, otherwise the region of no return.

2. Event Horizon Telescope

The first image of a black hole (*Figure* 1b) spurred tremendous interest among the scientific community regarding its immediate environment. Such an understanding is crucial to learn the dynamics of matter orbiting at near light speeds and under strong gravity effects in the proximity of a black hole. Hence, to address these and many other goals tied up with the GR, the Event Horizon Telescope (EHT) consortium was established. In this endeavour, the EHT adopted the technique of very long baseline interferometry[1] (VLBI) at short wavelengths. The technique involves linking the signals from various radio telescopes across the globe to create an interferometer of the size of the Earth. The telescopes part of the EHT network is shown in *Figure* 2. By leveraging the VLBI technique using novel systems, the EHT has virtually formed a network with angular resolution excelling any other telescope on the Earth. These technological advancements facilitate the study of supermassive black holes at an unprecedented angular resolution and sensitivity.

[1] Padmanabh Shrihari Sarpotdar, Introduction to the Techniques of Interferometry and Lunar Occultation in Radio Astronomy, *Resonance*, Vol.23, No.12, pp.1367–1373, 2018.

3. Important Objectives

One of the primary objectives of the EHT is to understand the effect of GR from the shadow of the black hole. As per the pre-

Figure 2. Radio telescopes that are part of the Event Horizon Telescope Array.

diction of GR, in-falling gas onto a black hole emits photons travelling along curved trajectories. This motion creates an illusion of a ring of light around a shadow, which corresponds to the location of the black hole. The term shadow here is attributed to the silhouette of the black hole, whose presence is emancipated by the bright ring of light caused by strong space-time effects. The equations of GR can provide an estimate of the size and shape of the black hole. These parameters are affected by the mass of the black hole, and to a lesser extent by its spin. It is also essential to test the shape cast by the black hole shadow as alternative theories of gravity predict different geometries.

The fundamental aspect of the evolution of a black hole is the process of 'accretion'[2]. The accretion of matter governs the growth of a black hole by losing gravitational energy. Friction heats up different parts of the disk surrounding the black hole and plays a vital role during this process. Accretion provides brightness to

[2]The gradual accumulation of particles/matter.

the radiation from the black hole, which despite being very massive is compact in geometry in comparison to the galaxy. The light radiated from these central regions of the galaxy can thus outshine the radiation emitted by all the stars put together in the same system.

The centre of our galaxy hosts a supermassive black hole, named Sagittarius A*.

The centre of our galaxy hosts a supermassive black hole, named Sagittarius A* (Sgr A*). This black hole, unlike most others found in bright galaxies, is not massive. However, owing to its proximity, it presents itself as the biggest supermassive black hole and hence is an important observational candidate for the EHT observations. The other best supermassive black hole candidate resides in the nearest giant elliptical galaxy Messier 87 (M87). Current observations suggest that the black hole in M87 is about 6 billion times massive than our Sun and about 1500 times than Sgr A*. Despite the massive black hole in M87, owing to its distance, the size appears relatively smaller than that of Sgr A*.

4. First-ever Black Hole Image

The EHT observations carried out in April 2017 at a wavelength of 1.3 mm (corresponds to 230 GHz) produced the first-ever horizon-scale structures of the supermassive black hole in M87. An enormous amount of effort was dedicated to the calibration and imaging procedures which took nearly two years.

The EHT observations carried out in April 2017 at a wavelength of 1.3 mm (corresponds to 230 GHz) produced the first-ever horizon-scale structures of the supermassive black hole in M87. An enormous amount of effort was dedicated to the calibration and imaging procedures which took nearly two years. Despite the uniqueness of these observations, the crucial element is the sparse coverage of the observables which makes any image production task difficult. To circumvent these issues, the current radio interferometric imaging technique was tested against whole new state-of-the-art sparse reconstruction ones. After several months of robust testing of the data, a superior agreement on images generated by all the methods was reached. The final consensus image (shown in *Figure* 3) was chosen as the average of the images produced by three different algorithms. The diameter of the ring obtained was estimated to be $42 \pm 3\ \mu$as.

Following the images, a plethora of general relativistic magneto-hydrodynamic simulations were performed under different phys-

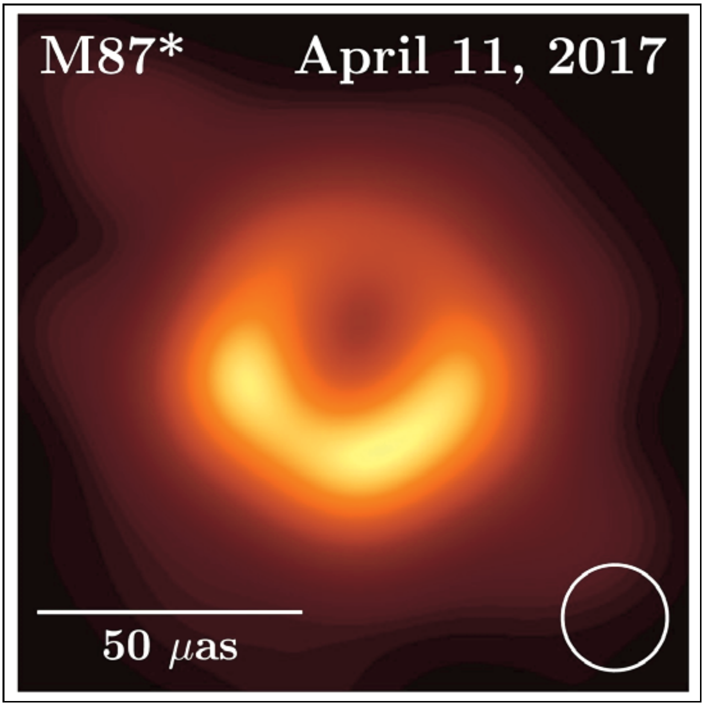

Figure 3. First-ever image of the supermassive black hole in M87. The image is produced from an average of the results generated by three different algorithms. The diameter of the ring is about 42 μas.

ical conditions to test the mass and other physical characteristics of the black hole. These results rendered the mass of the black hole as $(6.5 \pm 0.7) \times 10^9$ times the mass of the sun. Another important finding from these simulations is the spin of the black hole. The simulations indicate that the spin is pointed away from us (clockwise direction). This effect is evident from the brightness of the southern part of the ring, which as a result of the relativistic motion of the material seems brighter than other regions along the ring.

The EHT observations have resulted in the first-ever image of the supermassive black hole and have demonstrated the feasibility of imaging such extreme environments at millimetre wavelengths.

5. Summary

The EHT observations have thus resulted in the first-ever image of the supermassive black hole and have demonstrated the feasibility of imaging such extreme environments at millimetre wavelengths. The size estimate of the shadow of the black hole seems to resemble the predicted value caused by the extreme scattering of light. The addition of further telescopes to the existing array and improving the stability of observations in the next couple of years will shed light on the accuracy of the results obtained. It is essential to test the results obtained from these observations over the next decade to ensure that the results are unaffected by the variability of the source. Ongoing analyses of the EHT consortium includes the study of the magnetic fields around the black holes through polarimetric analyses, and in addition, the generation of the first image of the Sgr A*.

6. Indian Contribution

The EHT consortium comprises about 200 researchers from twenty countries across the globe, and ten Indian researchers are members of this consortium.

The EHT consortium comprises about 200 researchers from twenty countries across the globe. Ten Indian researchers are members of this consortium who are currently based in Chile, Germany, South Africa and the USA. The experience level of these Indian researchers ranges from doctorate students to professors. About seven of them were involved in the 2017 observation campaign at different locations that were part of the array experiments. Four researchers contributed to the calibration, imaging, and theoretical simulation practices. Some of the outstanding contributions by the Indian researchers to this project are in the development of state-of-the-art calibration and imaging techniques. These are pivotal to these observations as the data is very sparse compared to any normal radio interferometric observation, thus demanding more sophisticated mathematical procedures. These Indian researchers are also leading projects that target the nearby active galaxies with the possibility of imaging their black hole shadows in the near future.

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Suggested Reading

[1] **https://eventhorizontelescope.org/**

[2] **The Event Horizon Telescope Collaboration *et.al.*, *The Astrophysical Journal Letters*, Vol875, No.9, L1–L6, April 2019.**