Black Holes: From Concept to Reality

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Capturing a black hole’s image requires far more than just a point-and-shoot approach. It needs simultaneous observation by a global network of radio telescopes to achieve the feat.

Here is the first direct image of a supermassive black hole. Captured by the Event Horizon Telescope, the image shows the bright, spinning disk of material around the galaxy M 87’s supermassive black hole. Due to the intense gravity near black holes, the appearance of the disk is warped. This supermassive black hole is so large that the ‘event horizon’ or the point-of-no-return area around it – from where light and matter start falling into the black hole – is as big as our solar system. (Credit: EHT Collaboration)
Tremendous excitement among the world scientific community on 10 April 2019 when, at six simultaneous press conferences around the globe, astronomers announced they had accomplished the seemingly impossible: taking a picture of a black hole – a cosmic monster so voracious that even light cannot escape its clutches.

The image showed the supermassive black hole at the centre of the galaxy M87, a supergiant elliptical galaxy in the constellation Virgo some 53.5 million light-years from Earth. “We have taken the first picture of a black hole,” the Event Horizon Telescope (EHT) project’s director, Sheperd Doeleman, said in a news release. “This is an extraordinary scientific feat accomplished by a team of more than 200 researchers.”

Indeed, this is the first image of a real black hole; all previous images of black holes we have seen were computer simulations. This long-sought image provides the strongest evidence to date for the existence of black holes and opens a new window into the study of black holes, their event horizons, and gravity.

It must be made clear at the outset that black holes are not any kind of “holes”, rather they are regions of space-time where matter is so compressed that it creates an extremely strong gravity field from which even light cannot escape. In the present case, the image does not show the black hole itself but its “shadow”. When the light disappears behind the event horizon, we see a dark shadow there, with a bright ring formed as light bends in the intense gravity around the black hole forming the accretion disc.

“If immersed in a bright region, like a disc of glowing gas, we expect a black hole to create a dark region similar to a shadow – something predicted by Einstein’s general relativity that we’ve never seen before,” read a statement released by Heino Falcke, Chair of the EHT Science Council. “This shadow, caused by the gravitational bending and capture of light by the event horizon, reveals a lot about the nature of these fascinating objects and allowed us to measure the enormous mass of M87’s black hole,” the statement read.

The scientists said the image shows the black hole is about 100 billion kilometres wide, which is larger than the solar system, and weighs as much as 6.5 billion Suns.

The breakthrough was also announced in a series of six papers published in a special issue of The Astrophysical Journal Letters. According to the published papers, the structure of the black hole is nearly circular, as predicted by Einstein’s theory of general relativity, meaning the theory has passed yet another stringent test.

Before going further, it would be prudent to make it clear that the image that was released was not a “photograph” in the conventional sense. It was not captured in visible light by pointing a telescope at the object, as is done in conventional photography. Rather the image was “created” by computers after processing huge volumes of data gathered by a worldwide network of radio telescopes over several months. The result resembles a supermassive black hole and its halo, as it would appear if it were visible.

**Concept of Black Holes**

Black holes are extraordinary cosmic objects with enormous masses but extremely compact sizes. The presence of these objects affects their environment in extreme ways, warping space-time and super-heating any surrounding material.

Albert Einstein first predicted black holes in 1916 with his general theory of relativity. The term “black hole” was coined more than 50 years later in 1967 by American astronomer John Wheeler, and the first one was discovered in 1971.

Of course, black holes cannot be seen because they do not emit light, but their strong gravitational pull on matter around them gives a clue to astronomers about their presence and that is how numerous black holes have been discovered. Astronomers say there are so many black holes in the universe that it is impossible to count them.

Black holes have three “layers” – the outer and inner event horizon, and the singularity at the centre. The event horizon is the boundary around the black hole where matter or light loses its ability to escape; once a particle crosses the event horizon, it cannot leave.

The outer event horizon is the outer layer from which matter or light can escape while the second layer which is very hard to escape from is the inner event horizon. The singularity, according to theory, is a one-dimensional point at the centre of the black hole, which contains a huge mass in an infinitely small space, where density and gravity become infinite and space-time curves infinitely, and where the laws of physics as we know them cease to operate.

Of the three types of black holes that are known to exist, stellar black holes are the smallest. They are formed when hydrogen – the fuel that sustains the nuclear fusion reactors at their cores – is exhausted and they become unstable and collapse on themselves. But what happens at the end depends on the mass of the collapsing star. Medium-mass stars like our Sun would just collapse into a white dwarf. But some of the most massive ones explode into a supernova and then collapse down into neutron stars, or black holes.

We know this because of the work of Subrahmanyan Chandrasekhar – an Indian-born astrophysicist who spent 50 years at the University of Chicago and is most famous for coming up with the theory that explains the death of the universe’s most massive stars. He calculated that any star remnant with more than 1.4 times the mass of our Sun (known as the Chandrasekhar Limit) would be too massive to form a stable white dwarf. Beyond that limit, the force of gravity would cause the white dwarf to collapse further.

Before Chandrasekhar, it was believed that all stars collapsed into white dwarfs when they died, but he determined this was not so. However, at the time of his discovery in the 1930s, Chandrasekhar didn’t know what exactly these massive stars would turn into once they exhausted all their fuel.

Initially, Chandrasekhar’s idea was met with ridicule. Sir Arthur Eddington, an English physicist and astronomer who performed the first experimental test of Albert Einstein’s general theory of relativity.
and proved it right, openly mocked Chandrasekhar’s theory at a meeting of the Royal Astronomical Society in 1935. “I think there should be a law of Nature to prevent a star from behaving in this absurd way!” he is said to have said. Of course, he was wrong, but that is now history.

In 1939, American physicist Robert Oppenheimer and two of his collaborators (George Volkoff and Hartland Snyder) demonstrated that a star remnant with a mass greater than 1.4 solar masses would collapse until it was reduced to a singularity. However, Oppenheimer and his collaborators’ work received little attention and it was ignored for more than two decades.

In the mid-1960s, British mathematician and physicist Roger Penrose and physicist Stephen Hawking applied powerful mathematical techniques to this question and demonstrated that such singularities were inevitable when a star collapsed, provided certain conditions were met.
It was Hawking’s investigation of black holes’ nature that would prove revolutionary. In 1975, he published a shocking result according to which if one takes quantum theory into account, black holes wouldn’t be quite black! Instead, they should glow faintly with “Hawking radiation”, consisting of photons, neutrinos, and to a lesser extent all sorts of massive particles. This radiation is presumed to come from “virtual particles”, which are constantly popping into and out of existence in the bizarre quantum realm. They do so in matter-antimatter pairs, one of which has positive energy and the other negative energy.

This has never been observed, but most physicists believe the emissions exist. It has not been observed because the only black holes we have evidence for are those with lots of hot gas falling into them, whose radiation would completely swamp this tiny effect. Maybe, only for very small black holes would this radiation be significant.

Stellar black holes have masses ranging from about five to several tens of solar masses. In comparison, supermassive black holes can be millions or even billions of times as massive as the Sun, but have a radius similar to that of the Sun. Such black holes are thought to lie at the centre of almost every galaxy, including the Milky Way.

Scientists are still not sure how such massive black holes are formed, but they speculate that once formed, they gather mass from the dust and gas around them, material that is plentiful in the centre of galaxies, allowing them to grow to enormous sizes. Supermassive black holes may also be the result of hundreds or thousands of tiny black holes that merge together. Large gas clouds could also be responsible, collapsing together and rapidly accreting mass. A third possibility is the collapse of a stellar cluster, a group of stars all collapsing together.

As mentioned earlier, a black hole’s event horizon is the boundary defining the region of space around a black hole from which nothing (not even light) can escape. In other words, the escape velocity for an object within the event horizon exceeds the speed of light. And this makes black holes very difficult objects to photograph.

That is why the first image of a black hole released by the EHT team, is actually an image of the black hole’s outer event horizon – the minimum distance from the black hole’s centre where gravity is still weak enough for light to escape. Capturing a black hole’s image requires far more than just a point-and-shoot approach. It needs simultaneous observation by a global network of radio telescopes to achieve the feat.

**EHT – A Global Effort**

The Event Horizon Telescope (EHT) is a consortium of more than 200 scientists that has been working for about two decades. The project takes its name from a black hole’s famed point of no return – the event horizon. It is therefore impossible to photograph the interior of a black hole. So, the EHT imaged the event horizon, mapping out the black hole’s dark silhouette. (The disk of fast-moving gas swirling around and into black holes emits lots of radiation, so such silhouettes stand out.)

The EHT project has been scrutinising two black holes—the M87 behemoth, with about 6.5 billion times the mass of the Sun, and our own Milky Way galaxy’s central black hole, known as Sagittarius A*. This latter object, while still a supermassive black hole containing 4.3 million solar masses, is a pigmy compared to M87’s massive black hole. Both these objects are tough targets because of their immense distance from Earth. Sagittarius A* lies about 26,000 light-years from us, and M87’s black hole is a whopping 53.5 million light-years away.
M87’s supermassive black hole packs the mass of several billion Suns into a surprisingly tiny volume. And a seven-year study with the Hubble Space Telescope caught this invisible entity firing a powerful jet of high-energy particles out at nearly the speed of light, shooting them roughly 5,000 light-years into space.

In the present case, the worldwide team of researchers constructed the M87 black hole’s image using a technique called very long baseline interferometry (VLBI), which combines observations from multiple telescopes into one image. When separate dishes simultaneously observe the same target, scientists can collate the observations and “see” an object as though they’re using one giant dish that spans the distance between those telescopes. Functioning as one Earth-sized telescope, the network can resolve objects just one-ten thousandth the angular size of what Hubble can see. This technique let the astronomers glimpse finer details than even the Hubble Space Telescope can.

To get the job done, EHT scientists asked researchers around the world to point their radio telescopes at a select group of black holes and then combined the observations. The data to create the black hole image were collected by eight radio telescopes from around the world – located in Hawaii, Chile, Mexico, Spain, Arizona, and Antarctica.

As the Earth turned, each telescope set its sights on M87 and the other targets, stockpiling data. By the end of the observing run, the observers had filled half a ton of hard drives with 5 petabytes of data – “the equivalent of 5,000 years of MP3 files, or the entire selfie collection over a lifetime for 40,000 people.” (1 petabyte is equal to one thousand million megabytes.)

To complement the EHT findings, several NASA spacecraft were part of a larger effort, coordinated by the EHT’s Multiwavelength Working Group, to observe the M87 black hole using different wavelengths of light. As part of this effort, their models of the jet and disk around the black hole with the EHT observations. Other insights may come as researchers continue to pore over these data.

**Processing Petabytes of Data**

Since the volume of the data was enormous, it could not be processed online. So, the team air-freighted these hard drives to Massachusetts (USA) and Germany, where the eight radio telescopes’ observations were fed into supercomputers and aligned to within trillionths of a second. “They have to be exactly right,” said Michael Johnson of Harvard-Smithsonian Astrophysics Centre of Harvard University, who helped coordinate the imaging data analysis. “If they’re even a tiny bit off, you see nothing.”

A 29-year-old MIT graduate Katie Bouman played a key role in the whole process. In 2016, she developed an algorithm named CHIRP (Continuous High-resolution Image Reconstruction using Patch priors) to sift through the mountain of data gathered by the EHT project from telescopes around the world and create an image of a supermassive black hole for humanity. To guarantee the accuracy of the image, the Harvard-Smithsonian Astrophysics Centre gave the data to four different teams. Each team independently used the algorithm to obtain an image. After a month of work, the four groups presented their results to the other teams.

After the image was released, Bouman said in a post, “It required the amazing talent of a team of scientists from around the globe and years of hard work to develop the instrument, data processing, imaging methods, and analysis techniques that were necessary to pull off this seemingly impossible feat.”

Although the black hole image released on 10 April 2019 is based on only four days of observations, EHT scientists spent
years testing and installing equipment, working in the thin air of the remote Chilean desert and braving the cold of Antarctica. They built computer algorithms and developed simulations of what they might see. They did dry runs, agonising over go/no-go weather conditions at eight telescopes at six geographic sites scattered from Hawaii to Spain and Arizona to the South Pole.

It may be mentioned here that the EHT measures wavelengths in the millimetre regime, too long to be visible to the human eye, but ideally suited to the task of imaging a black hole. The gas surrounding the black hole being almost transparent at this wavelength, the waves travel to Earth almost undisturbed. Since our eye cannot see light of such wavelengths, the released EHT image shows the observed signals shifted to the visible range.

According to the scientists, the new results should help scientists get a better handle on black holes. For example, the EHT imagery will likely shine significant light on how gas spirals down into a black hole. This accretion process, which can lead to the generation of powerful jets of radiation, is poorly understood at present. In addition, the shape of an event horizon can reveal whether a black hole is spinning. In the present case, EHT’s data revealed the M87 black hole is spinning clockwise, team members said.

The scientists said the project should also show how matter is distributed around a black hole, and EHT observations could eventually teach astronomers a great deal about how supermassive black holes shape the evolution of their host galaxies over long time scales. EHT’s results also mesh well with those of the Laser Interferometer Gravitational-wave Observatory (LIGO), which has detected the space-time ripples generated by mergers involving black holes just a few dozen times more massive than the Sun.

According to the EHT team, this first image will be studied and analysed for years to come, but the EHT is just getting started. “Now that it’s possible to resolve the area around a black hole lurking in the core of a galaxy, we can expect to eventually capture images of other black holes beyond M87,” it said.

The M87 black hole is officially designated as M87+, but it has also been given the name Pōwehi, which means “embellished dark source of unending creation” in the indigenous Hawaiian language. However, before the name is officially recognised by astronomers around the world, it must be approved by the International Astronomical Union (IAU).

By directly imaging M87’s supermassive black hole and accretion disk, researchers are already gaining insight into the complex processes that shape the jets of active galaxies. And since powerful, jet-spewing supermassive black holes tend to be more prevalent in the early universe, these insights may just reveal new discoveries into how our young cosmos evolved.

According to the EHT team, by 2020 there will be more observatories to work with. The Greenland Telescope joined the consortium in 2018, and the Kitt Peak National Observatory outside Tucson, Arizona, USA, and the NOrthern Extended Millimetre Array (NOEMA) in the French Alps will join EHT in 2020. These extra eyes may be just what’s needed to bring black holes into even greater focus, it said.

Once thought to be figments of theorists’ wildest imaginations, black holes are now known to be a reality and crucial players in the cosmic scenario, profoundly affecting the formation and evolution of stars and galaxies across the universe. And all this has been made possible by human ingenuity, technology and dedicated teamwork.

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