U.S. HOUSE OF REPRESENTATIVES
COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY
HEARING CHARTER

Event Horizon Telescope: The Black Hole Seen Round the World

Thursday, May 16, 2019
10:00 am – 12:00 pm
2318 Rayburn House Office Building

PURPOSE

On Thursday, May 16, 2019 at 10:00 am, the Committee on Science, Space, and Technology will hold a hearing to review the scientific knowledge gained from the very first image of a black hole; how this new imaging capability may enable yet more scientific discovery; how the image was created, including the domestic and international partnerships that made this result possible; and future plans for the Event Horizon Telescope.

WITNESSES

- **Dr. France Córdova**, Director, National Science Foundation
- **Dr. Sheperd Doeleman**, Director, Event Horizon Telescope; Center for Astrophysics | Harvard and Smithsonian
- **Dr. Colin Lonsdale**, Director, MIT Haystack Observatory
- **Dr. Katherine (Katie) Bouman,** Postdoctoral Fellow, Harvard-Smithsonian Center for Astrophysics

BACKGROUND

In April 2017, a group of eight telescopes at different sites around the world were synchronized to observe radio waves emanating from the center of a galaxy called Messier 87 (M87). Together, these telescopes make up the Event Horizon Telescope (EHT), a global project with the goal of capturing the first-ever image of a black hole. Leaders of the EHT project, a collaboration of more than 200 scientists, revealed their first result on April 10, 2019.

Black Holes

Einstein's theory of general relativity postulates that gravity is not a force, as described by Newton, but a geometric bending, or distortion, of space-time.[1] Any massive object creates a distortion in the space-time around it. The higher the curvature of this distortion, the stronger the

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[1] Space-time is a four-dimensional continuum composed of three-dimensional space and one-dimensional time.

"pull" of gravity. A black hole is an extreme case in which the curvature of space-time is infinite. At a sufficiently close distance to a black hole, the gravitational pull is so strong that nothing, not even light, can escape. This "point-of-no-return" is called the event horizon.

Black holes generally come in two varieties, stellar-mass and supermassive. Stellar-mass black holes are around 3-10 times the mass of the Sun and are scattered throughout the Milky Way and other galaxies. Supermassive black holes are millions to billions of times the mass of the Sun and lie at the centers of galaxies. Most galaxies are thought to host a supermassive black hole in their center, including our own Milky Way galaxy. Studying supermassive black holes can help us understand how galaxies form and evolve over time and to test Einstein's theory of general relativity in the most extreme conditions.

Black holes were once considered to be a mathematical artifact of Einstein's theory, not real objects. Even Einstein had doubts about the reality of black holes. Since black holes emit no light of their own, scientists examine the gravitational effects black holes have on nearby matter and light.

In recent years, evidence of the existence of black holes has been mounting. For instance, by tracking the orbital motion of stars in the innermost region of the Milky Way, scientists have determined that an object with a mass equal to 4 million Suns and a size smaller than twice that of Pluto's orbit lies at the center of our galaxy. [2] Most scientists now agree that this central object can only be a supermassive black hole.[3] In the M87 galaxy, NASA's Hubble Space Telescope observed gas clouds orbiting rapidly about the galaxy's center, indicating the presence of a black hole about 6 billion times the mass of the Sun.[4,5]

Despite the growing body of indirect evidence that black holes exist, a black hole had never been directly imaged until the EHT. By definition, black holes are invisible. If a black hole is surrounded by light-emitting material, however, general relativity predicts that this material should cast a "shadow," or an outline of the black hole and its event horizon. The goal for the EHT was to image this shadow.

Event Horizon Telescope

One of the targets for the 2017 EHT observing run was the supermassive black hole at the center of the M87 galaxy. While very massive, the black hole at the center of M87 is small in astronomical terms, about the size of our solar system. It's also far away, about 55 million light-years from Earth. To resolve something that small from such a large distance requires a telescope impossible to build, as it would have to be about the size of Earth.

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[2] Ghez, Andrea M. *et al*., "High Proper-Motion Stars in the Vicinity of Sagittarius A*: Evidence for a Supermassive Black Hole at the Center of Our Galaxy," https://iopscience.iop.org/article/10.1086/306528

[3] The black hole at the center of the Milky Way galaxy is called Sagittarius A*.

[4] Walsh, Jonelle L. *et al*., "The M87 Black Hole Mass from Gas-dynamical Models of Space Telescope Imaging Spectrograph Observations," https://iopscience.iop.org/article/10.1088/0004-637X/770/2/86

[5] The black hole at the center of the M87 galaxy is called M87*.

To get around this, the EHT team used a technique called very-long-baseline interferometry (VLBI). VLBI combines data collected simultaneously at multiple telescopes around the world to emulate a telescope the size of their separation (baseline). VLBI only works for radio waves, or a type of light with wavelengths longer than infrared light (1 millimeter to 100 kilometers). Fortunately, radio waves are also the only type of light that can travel unimpeded by dust and gas all the way to Earth from the center of M87.

Source: https://www.sciencenews.org/editors-picks/event-horizon-

Eight telescopes in six locations around the globe participated in the 2017 observations, their operations perfectly synchronized with the help of atomic clocks.

- SMT[6] in Arizona
- JCMT[7] and SMA[8] in Hawaii
- LMT[9] in Mexico
- ALMA[10] and APEX[11] in Chile
- IRAM[12] in Spain
- SPT[13] in Antarctica

By collecting data in unison and stitching it together, the EHT array acts like a single Earth-sized telescope with enough resolving power to read the date on a coin in Los Angeles from New York City. This is an unprecedented resolution for astronomy, more than 1,000 times better than that of the Hubble Space Telescope.[14]

Combining the Data

Each telescope of the EHT produced enormous amounts of data – about 350 terabytes per day – which was stored on high-performance hard drives. The team collected so much data (5 petabytes[15] in total) that the hard drives had to be shipped via FedEx from their respective

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[6] http://aro.as.arizona.edu/

[7] https://www.eaobservatory.org/jcmt/

[8] https://www.cfa.harvard.edu/sma/

[9] http://www.lmtgtm.org/

[10] https://www.almaobservatory.org/en/home/

[11] http://www.apex-telescope.org/

[12] https://www.iram-institute.org/EN/30-meter-telescope.php?ContentID=2&rub=2&srub=0&ssrub=0&sssrub=0

[13] https://pole.uchicago.edu/

[14] NSF, "Planet-sized 'virtual telescope' expands to the South Pole to observe black holes in detail," https://www.nsf.gov/news/news_summ.jsp?cntn_id=134758

[15] One petabyte contains 1 million gigabytes (GB). An iPhone has 64 GB of data storage.

telescopes to two sites for processing – MIT Haystack in Massachusetts and Max Planck Institute for Radio Astronomy in Germany. It would have taken 10 years to transfer all of the data over the internet.

At both locations, a highly specialized supercomputer, called a correlator, combined the data. Since each telescope is at a different position on Earth, each had a slightly different view of the black hole. Using time-stamps created by the atomic clocks at each site, the correlator matched up and compared the data streams from every possible pairing of EHT's eight telescopes. From these comparisons, the correlator eliminated the noise and identified the black hole signal. This signal is called a "fringe."

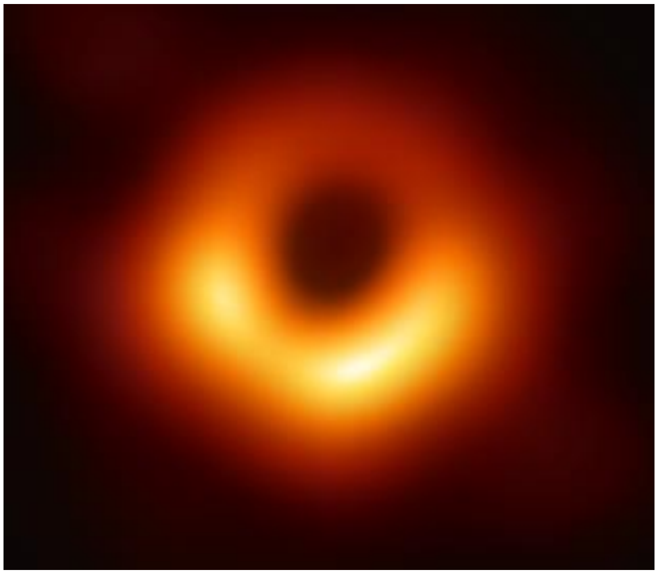
The alignment of the black hole signals from each telescope was further refined by identifying and correcting for minute timing perturbations at each observing site and rerunning the correlation until the data could be thoroughly verified.

Constructing the Image

The correlated data was then released to four separate imaging teams charged with constructing an image. The teams worked in complete isolation from each other in order to not influence each other's results. Each team developed its own imaging algorithms to convert the radio signals into visual images.

One of the biggest challenges for the imaging teams was that the data had huge holes in it. The eight telescopes in the EHT array provided coverage for only a small portion of the entire virtual Earth-sized telescope. There are an enormous number of images that could match the data collected at the eight sites.

To solve this problem, the teams used machine learning with synthetic data and data from other astrophysical objects to train their algorithms. The algorithms were trained to generate images that satisfied the data in the simplest possible way, weeding out images that were physically impossible or contained overly complicated features.



Source: https://eventhorizontelescope.org/

Once the imaging teams were confident in the accuracy of their algorithms, they ran them on the M87* data. When the teams compared the four images they constructed, they found that they were remarkably similar. The images were then blurred and averaged together to create the final result.

NSF Support

To achieve the M87 result, the EHT collaboration relied on National Science Foundation (NSF) investments of three types: investigator grants directly for EHT research and instrumentation; existing multi-user observatories and facilities; and long-term investments in the foundational techniques and facilities for radio astronomy, particularly VLBI. NSF has awarded $28 million across 22 grants for instrumentation and facility upgrades, data analysis, and theoretical modeling directly related to the EHT. The multi-user facilities and infrastructure built and/or operated at least in part with NSF funds included three of the eight telescopes used for the M87 result (ALMA, SMT, and SPT) and high-performance computing infrastructure used as part of the image processing and theoretical modeling.

The foundational techniques of radio astronomy, including VLBI, were developed through several decades of NSF investments, including in facilities like the Green Bank Observatory in West Virginia, the Very Large Array (VLA) and Very Large Baseline Array (VLBA) in New Mexico, and the Combined Array for Millimeter-Wave Astronomy (CARMA), which was decommissioned in 2012.[16]

Future Plans

During the 2017 observing run, the EHT team also collected data from the black hole at the center of the Milky Way galaxy, called Sagittarius A*. The EHT imaging teams are currently working to construct images from that data. Since the Milky Way galaxy is less active, meaning less material is flowing into the black hole, light from the region immediately outside of the event horizon varies on shorter timescales than the region outside the black hole in M87. This makes it more challenging to construct an image. The upside is that there is a potential for the EHT imaging teams to construct a video of these variations.

The EHT array expanded to include a ninth telescope for its 2018 observing run, the Greenland Telescope.[17] Unfortunately, the observations made in 2018 were compromised due to bad weather. For its 2020 run, the EHT will include two more telescopes – the Kitt Peak 12-meter telescope[18] in Arizona and the NOEMA Observatory[19] in France – for a total of 11 telescopes. The additional telescopes will allow the team to construct sharper images.

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[16] NSF, "History of NSF'S Early Support for Very Long Baseline Interferometry (VLBAI) and Black Hole Observations, 1966-1985," https://www.nsf.gov/news/special_reports/blackholes/PDFs/EHT_VLBI_History_v1.pdf

[17] https://www.cfa.harvard.edu/greenland12m/

[18] https://www.noao.edu/kpno/

[19] https://www.iram-institute.org/EN/noema-project.php