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Before the
Committee on Science, Space, and Technology
United States House of Representatives

on
"Event Horizon Telescope: The Black Hole Seen Round the World"

May 16, 2019

Chairwoman Johnson, Ranking Member Lucas, and Members of the Committee, thank you for holding this hearing, and for the opportunity to discuss the Event Horizon Telescope (EHT) collaboration and the resulting first direct visual evidence of a supermassive black hole, and its shadow. We are all very excited by this remarkable accomplishment, one that will transform and enhance our understanding of black holes. I want to focus my remarks today on EHT's history with the National Science Foundation (NSF), the vision and support of so many dedicated researchers, and what this discovery means for the future of science.

Black holes have captivated the imaginations of scientists and the public for decades. In fact, we have been studying black holes so long that sometimes it is easy to forget that none of us had actually seen one. We have simulations and illustrations, and thanks to instruments supported by NSF, we have detected binary black holes merging deep in space. We have observed the episodic transfer of matter from companion stars onto black holes. Some massive black holes are surrounded by particles and radiation we can observe. We have spotted subatomic materials flung across millions of light-years from near a black hole, but we had never actually directly seen the shadow of an event horizon, that point of no return after which nothing, not even light, can escape a black hole, until now. No single telescope on Earth has the sharpness to create an un-blurred definitive image of the black hole. This team did what all good researchers do, they innovated.

The Beginning...

More than six decades ago, NSF-funded researchers helped lead the development of radio astronomy. Beginning with the Green Bank Observatory in 1955 NSF has supported multiple radio astronomy facilities including: Arecibo Observatory in Puerto Rico (operations partly funded by NASA); the Very Large Array on the Plains of San Augustin in New Mexico; the

Very Long Baseline Array (operations partially funded by the U.S. Naval Observatory) with 10 field sites throughout the U.S. and the Virgin Islands; the Combined Array for Millimeter-wave Astronomy; and, most recently, the Atacama Large Millimeter/submillimeter Array (ALMA) in Chile.

The EHT observations were particularly dependent upon Very Long Baseline Interferometry (VLBI), which synchronizes telescope facilities around the world to form one huge, Earth-sized telescope. VLBI began in the late 1960s and this capability advanced as new radio telescopes were constructed. Research in this field was supported initially by NSF for astronomy and subsequently by NASA and other agencies for geodesy.

Observing at shorter wavelengths improves VLBI resolution, or "sharpness." Original VLBI observations operated at centimeter wavelengths. Building upon this early VLBI research, NSF supported the MIT Haystack Observatory in extending VLBI observations from centimeter wavelengths into the millimeter-wavelength regime. Currently, the EHT observes at 1.3 millimeters and achieves a resolution of 20 micro-arc seconds. This incredible resolution is equivalent to seeing a grain of sand on a beach in Los Angeles from a telescope in New York. It enabled the EHT to image a black hole.

Developments in computing and data storage technologies also helped make the EHT possible. One measure of progress is the data recording and processing rates, which determine the sensitivity of the observations, or the faintness at which celestial objects can be observed. Systems circa 1969 recorded data at 0.720 megabits per second (Mbit/s). Current EHT stations record at 64 gigabits per second (Gbit/s). This corresponds to a 90,000-fold increase in the data recording rates over the last fifty years! To put it another way, during its 2017 observing campaign, each element of the EHT downloaded data from the universe at more than one thousand times the speed of a broadband internet connection.

A natural consequence of using telescopes in different countries for VLBI was international collaboration. At the heart of VLBI lies the fact that no single telescope can accomplish alone what many telescopes can do together in unison. As it is for radio telescopes, so it is for the scientists who use them. Over the years, the EHT project grew from a small exploratory group to a large international collaboration. The current collaboration includes more than two hundred members from twenty different regions and countries. This team learned to take advantage of institutional, cultural, and individual diversity to unite around the common goal of imaging a black hole.

A key program in this international collaboration was NSF's Partnerships for International Research and Education program, which allows the agency to leverage U.S. dollars and improve scientific outcomes. A partnership project on black hole astrophysics led by the University of Arizona (with partners in Germany, Mexico, and Taiwan) contributed critical data on weather conditions at all EHT sites that enabled the 2017 EHT observations. The research team also developed the cloud computing infrastructure for the EHT's main post-processing system. Other funded activities involved detector development and fast data transfer.

Creating the EHT was a formidable challenge that required upgrading and connecting a worldwide network of eight pre-existing telescopes deployed at a variety of challenging, high-altitude sites. These locations included volcanoes in Hawai`i and Mexico, mountains in Arizona and the Spanish Sierra Nevada, the Chilean Atacama Desert, and Antarctica. The telescopes contributing to this result were ALMA, the Atacama Pathfinder EXperiment (APEX), the Institute for Radio Astronomy in the Millimeter Range (IRAM 30-meter telescope), the James Clerk Maxwell Telescope, the Large Millimeter Telescope Alfonso Serrano, the Submillimeter Array, the Submillimeter Telescope, and the South Pole Telescope. The ALMA telescope has the largest collecting area of any radio telescope and incorporating this telescope into the EHT array enabled its successful observations. Without federal funding of over $500 million to construct both the ALMA and South Pole Telescopes, EHT could not have imaged a black hole. Petabytes of raw data from the telescopes were processed by highly specialized supercomputers hosted by the Max Planck Institute for Radio Astronomy and MIT Haystack Observatory.

Throughout the history of astronomy, improved observations advanced our understanding of the universe. For example, precise naked-eye observations of the planets by Tycho Brahe and calculations by Johannes Kepler circa 1609 proved that Earth orbited the Sun, and that the planets orbited in ellipses. In modern times, the NSF Laser Interferometer Gravitational Wave Observatory functions by measuring the movement of test masses to extraordinary precision, less than an atomic diameter. This enabled detecting gravitational waves from distant colliding black holes and neutron stars. Improving observations requires new technologies. That is why, for more than thirty years, NSF has supported technology development for astronomy through the Advanced Technologies & Instrumentation (ATI) program. This program enables innovative ideas and transformative science such as the EHT. The ATI program supported EHT with eight separate awards that got the project started and sustained its early technical development. Without this early seed funding, the EHT could never have succeeded.

Supporting basic research has tremendous benefits for humankind. VLBI research had unanticipated, though obvious in hindsight, practical benefits. VLBI enabled exquisitely precise images of distant astronomical objects. These positions were used to anchor a celestial reference frame of coordinates against which the Earth itself could be compared. It measured the separations of its telescopes to millimeter accuracy. Since these telescopes were grounded on the Earth, the orientation and rotation of the Earth itself could now be measured with unprecedented accuracy. Nowadays VLBI observations of distant quasars are undertaken on a daily basis by the U.S. Naval Observatory. Their measurements are used to update the positions of satellites, in particular those of the Global Positioning System (GPS).

GPS has become ubiquitous for finding positions. Methods developed by VLBI researchers improved the accuracy and capability of GPS, and ushered in aircraft precision landing, vehicle positions and a host of other widely used applications. Everyone who uses a smartphone to find directions, search for a nearby restaurant or reserve a ride-share benefits from astronomy and decades of NSF and NASA-funded VLBI research.

NSF played a pivotal role in the EHT discovery by funding individual investigators, interdisciplinary scientific teams and radio astronomy research facilities since the inception of the EHT. It required expertise in areas ranging from detector development to high-performance computing and theoretical physics. Over the last two decades, NSF has directly funded twenty-two different awards totaling more than $28 million in EHT research, which is the largest commitment of resources for the project. Other supporters include international funding agencies, especially the European Research Council, as well as the Ministry of Science and Technology of Taiwan and others. Private foundations such as the Gordon and Betty Moore Foundation and the Templeton Foundation also supported the project.

It is important to note that the $28 million investment by NSF was complemented by billions of dollars of investments in infrastructure worldwide. As described above, this discovery would not have been possible without the construction of the South Pole and ALMA telescopes. The South Pole Telescope provided a key calibration capability and will be necessary for future observations. ALMA provided the necessary sensitivity to image the black hole. Because no other ground-based facilities have their unique capabilities, without each of them, the EHT could not have succeeded. Sustained support for the construction of new research infrastructure is critical to our ability to advance scientifically. Without this research infrastructure tens of thousands of scientists and students would not have the tools they need to make these great advancements.

The Present...

On April 10, 2019 NSF and EHT unveiled to the world the first image of a black hole, and the event horizon, outside of which matter and photons can escape and inside of which they are captured by the black hole This incredible moment caught the imagination of scientists and the public alike. The Washington D.C. press conference was viewed more than 1.2 million times, with at least 737,378 people watching the broadcast live. This resulted in 17,000 new subscribers to the NSF YouTube pages. The press conference was viewed live in universities and schools all over the world and more than over 400 broadcast news stories aired about the announcement. The NSF gained 25,000 new Facebook followers and 40,000 new Instagram followers in the days after the announcement. On April 11, one day after the public announcement, the image of a black hole appeared on the front pages of the New York Times, the Washington Post, the Wall Street Journal and many other newspapers around the world. These facts and statistics demonstrate the natural fascination and wonder that people everywhere have for astronomy.

How did we get here? Through the imagination and dedication of scientists around the world, willing to collaborate to achieve a daunting goal. Through world-wide investment in research infrastructure, technological development, and basic research. And finally, through long-term financial commitments from NSF and other funders, both here and abroad, willing to take risks in pursuit of an enormous potential payoff. Without international collaboration, the contributions of hundreds of scientists and engineers, and sustained, stable funding, the EHT would have been impossible.

The Future...

As we look to future discoveries, NSF has put forward bold questions – 10 Big Ideas - that will drive NSF's long-term research agenda -- questions that will ensure future generations continue to reap the benefits of fundamental science and engineering research. These 10 Big Ideas capitalize on what NSF does best: catalyze interest and investment in fundamental research, which is the basis for discovery, invention and innovation. They are meant to define a set of cutting-edge research agendas and processes that are uniquely suited for NSF's broad portfolio of investments, and will require collaborations with industry, private foundations, other agencies, science academies and societies, and universities.

Funding these ideas will push forward the frontiers of U.S. research and provide innovative approaches to solve some of the most pressing problems the world faces, as well as lead to discoveries not yet known. The EHT project aligns with three of NSF's 10 Big ideas. Future astrophysical discoveries will benefit from new hardware and software advances generated by *Harnessing the Data Revolution*, particularly development of a new data cyberinfrastructure for timely handling, processing, analysis and modeling of astrophysical data. By integrating new ways to probe the cosmos, *Windows on the Universe* is providing a more detailed view of the cosmos, and *Mid-Scale Research Infrastructure* offers a new funding mechanism that is responsive to ambitious projects like EHT requiring a dynamic, holistic, and flexible investment.

In particular, the large data generated by the EHT illustrated the need for basic research in math, statistics and computer science that will enable data-driven discovery through visualization, better data mining, machine learning and more. NSF's Big Idea: *Harnessing the Data Revolution* will support an open cyberinfrastructure for researchers and develop innovative educational pathways to train the next generation of data scientists. The EHT observations generated 5 petabytes of raw data from telescopes. It is equivalent to 100 years of high-definition YouTube videos. Such large quantities of data are most efficiently transported on physical media rather than over the Internet. Therefore, these data were ultimately stored on approximately one thousand hard drives that collectively weighed more than one half ton, costing approximately $3 million, and needed to be shipped across the globe for processing. Recording, storing, transmitting and processing these data were some of the key technical challenges that were overcome to successfully image a black hole. Increasingly in the future, science in general and radio astronomy in particular will generate tremendous volumes of data. Transforming these data into useful scientific knowledge will demand innovation and investment in new hardware and software that this Big Idea fosters.

In successfully imaging a black hole, the EHT captured the imagination of the general public to these enigmatic objects. It is yet another example that NSF-funded research brought popular attention to black holes and Einstein's theory of relativity. It follows on the discovery of gravitational waves from colliding black holes, supported by NSF for four decades, as well as numerous observations of black hole phenomena with NSF telescopes. The gravitational wave discovery was recognized with the 2017 Nobel Prize in Physics and ushered in a new discipline of multi-messenger astronomy. This discipline combines data from traditional telescopes that receive electromagnetic radiation with data from gravitational wave charged particles and/or

neutrinos in an integrative view of astrophysical events. The *Windows on the Universe* Big Idea supports this integrative approach. It is a natural extension of the multiwavelength approach that astronomers have increasingly adopted in recent decades, whereby data from X-ray, optical, infra-red, submillimeter and radio wavebands of the electromagnetic spectrum are used to form a more complete picture of astrophysical processes than either waveband could reveal in isolation.

The success of the EHT also highlights the need for *Mid-Scale Research Infrastructure*. From its inception, the EHT was awarded twenty-two separate awards from five different NSF programs. Each award was the result of a separate proposal submission and competition. This substantial churn of the proposal writing and review process over a 19-year period was clearly ultimately successful. After more than a decade of development and piecemeal funding, the project was reviewed as a whole in our Division of Astronomical Sciences mid-scale program and received the final $6.5 million in funding that resulted in the successful set of observations. NSF support of mid-scale research concepts will enable more effective support of comparably sized scientific projects in the future.

This discovery would never had been possible without the global cooperation and coordination of the EHT. The United States led this international collaboration, showing the pioneering, trail-blazing spirit upon which our country was founded. Continued close cooperation with our international partners is key to taking the science to the next level.

In producing the first image of a black hole, the EHT has inspired the general public and generated a global phenomenon. The majesty of discovering our universe motivates such ambitious experiments, but as with all fundamental science, EHT offers other important benefits. This science will advance education, inspiring students and developing the workforce our society requires. It has, and will continue, to lead to collaborations in astrophysics, engineering, computer science and other fields. Astronomy is a point of entry for students and young people into Science, Technology, Engineering, and Mathematics (STEM). STEM education is an increasingly important part of the educational system. It prepares students for satisfying, well-paying jobs in a competitive, global workforce. Most of these jobs will not be in scientific research; however, the technical and critical-thinking skills of a STEM education are invaluable. Science and technology are drivers of the national economy. As such, the future prosperity of the U.S. depends in part upon motivating the next generation to be curious, to explore, and to learn and grow in the context of STEM. Astronomy is a crucial source of inspiration for this process.

We often say that NSF is where discoveries begin. It is also where many discoverers receive the support they need to make the next leap in their research careers. The ATI program, out of which the EHT began, trains early career scientists and develops them into the next generation of leaders of large and complex scientific projects and facilities. Programs like the Graduate Research Fellowship Program and the CAREER program, which support the next generation of researchers are also critically important. They invest in individuals who are poised to push their fields of study further. Equally important are our efforts to broaden participation and diversity in STEM. NSF has taken many steps in recent years to on both these fronts – from instituting our INCLUDES program as one of the Big Ideas, to issuing new terms and conditions on

harassment. There is no room for discrimination in science and our continued leadership in innovation depends on us recognizing and drawing upon the full potential of our population.

In Summary...

Madam Chairwoman, this discovery is historic for astrophysics, and incredibly meaningful for me personally as an astrophysicist. We have seen what was before unseeable. Black holes have sparked imaginations for decades. They have exotic properties and are mysterious to us. Yet with more observations like this one they are yielding their secrets. This is why NSF exists. We enable scientists and engineers to illuminate the unknown, to reveal the subtle and complex majesty of our universe.

Basic research can be risky in the short term, but in the long term it is a certain path to revolutionary progress. The Event Horizon Telescope shows the power of collaboration, convergence, shared resources, and commitment to developing the technologies that enable discovery. These allow us to tackle the universe's biggest mysteries. All the contributors to EHT: Scientists, NSF, and Members of Congress, should take enormous pride in our collective accomplishment. Were it not for the support of Congress and the investment of taxpayer funding, this would not have been possible. With this discovery we can move forward with the science of understanding our universe —pushing the boundaries of discovery and innovation still further.

Thank you again for your continued support for NSF's mission and for holding this hearing today and the opportunity to testify. I will be pleased to answer any questions you may have.