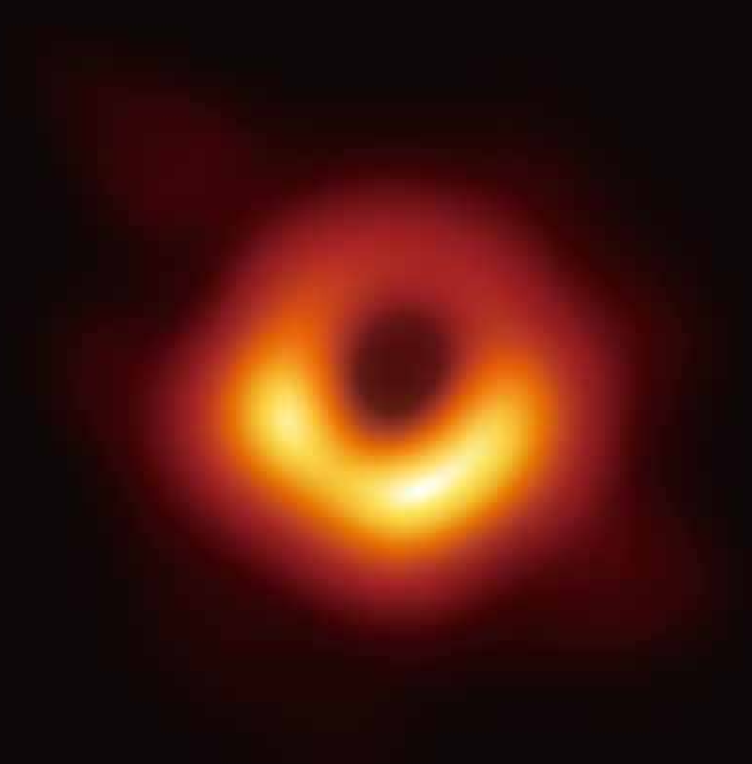
Seeing a Black Hole: A Global Effort

By SONG Jianlan (Staff Reporter)



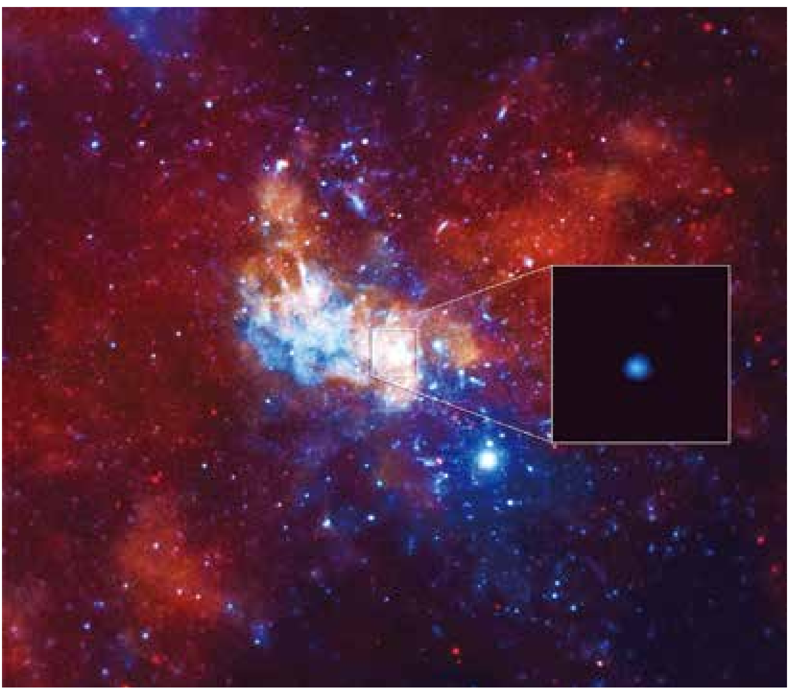
A look of the heart of Messier 87 (M87) from 55 million years ago: Astronomers from around the world managed to "see" the supermassive black hole at M87, an elliptical galaxy 55 million light years away from us. It gives clues about how this black hole looked like 55 million years ago, a time when no hominid is known to have walked on the Earth. The southern part of the circle looks brighter due to Doppler effect: As the matter surrounding the black hole moves towards the Earth from the south and further flies away from the Earth in the north. Judging from the image, the diameter of the event horizon shadow of M87 is as large as 100 billion kilometers. (Credit: Event Horizon Telescope Collaboration)

"Seeing is believing." But we had never "seen" a black hole, until 9:07 pm (GMT+8) on April 10, 2019 when a serial of globally-simultaneous releases unveiled the image of a supermassive one at the heart of Messier 87 (M87), a galaxy 55 million light years away from our home planet.

At last, this portrait – from 55 million years ago – manifests as the most direct evidence so far for the existence of supermassive black holes. This image has resulted from a four-day-long observation by an array of eight ground-based radio telescopes called "Event Horizon Telescope" (EHT). Mutually connected with each other, this array is virtually equivalent to a camera as big as the Earth. As a global teamwork involving astronomers from multiple continents, the EHT project culminates the centennial effort of human beings to recognize and understand this extreme phenomenon in the cosmos.

A total of 13 partner institutions worked together to create the EHT, using both pre-existing infrastructure and support from a variety of agencies. Key funding has come from the US National Science Foundation (NSF), the EU's European Research Council (ERC), and also funding agencies in East Asia.

"We have taken the first picture of a black hole," said EHT project director, Sheperd S. Doeleman of the Center for Astrophysics | Harvard & Smithsonian. "This is an extraordinary scientific feat accomplished by a team of more than 200 researchers."



The center of the Milky Way as "seen" in a radio astronomical observation on January 5, 2015. Sagittarius A* appears as a bright point-like radio source, indicating the existence of a supermassive black hole. (Credit: NASA/CXC/Stanford/I. Zhuravleva *et al.*)

This breakthrough came together with a series of six papers published in a special issue of *The Astrophysical Journal Letters*.

The M87 black hole has a mass about 6.5 billion times that of the Sun, which renders it an "apparent size" only second to the Sagittarius A* (Sgr A*), which is much closer to us (only about 26,000 light years away), located at the center of our home galaxy, the Milky Way. Unlike Sgr A*, it is not overshadowed by much interstellar gases; though both M87 and Sgr A* were chosen as main targets for EHT.

At 21:07 (GMT+8), Prof. SHEN Zhiqiang, director of the Shanghai Astronomical Observatory (SHAO), CAS, announced the official publication of the image at the Shanghai release, one of the seven press conferences that occurred in coordination across the globe. Along with many institutions under the Chinese Academy of Sciences (CAS), SHAO is an affiliated institution of the EHT project. The Center for Astronomical Mega-Science (CAMS) of CAS has been supporting EHT project as a member institution of one of its stakeholders. CAMS has been established by integrating three major astronomical observatories under CAS, namely the National Astronomical Observatories (NAOC), the Purple Mountain Observatory (PMO), and SHAO. SHAO took the lead in organizing and coordinating researchers at CAS to participate in the EHT collaboration.

Einstein Was Right, Again

In the absence of any picture of a black hole, we have believed in their existence for around a century – never without disputes, though.

This long-awaited picture shows us a ring-like "shadow" of the black hole, just as what Albert Einstein's theory of general relativity predicted. Before that, in his theory of special relativity, he had integrated space and time into a four-dimensional spacetime continuum, and suggested that gravity could be seen as the twist or distortion of this continuum. Now in his theory of general relativity, he further predicted that an object could collapse into an extremely tiny volume, squeezing its own mass into an extremely small sphere termed "event horizon (EH)." When this happens, as a result from the extremely high density of mass, the twist of the spacetime continuum inside its EH could go unlimitedly intensive. In other words, the gravity inside this EH could go unlimitedly large – so large that even light would not be able to escape from its pull.

This great physicist put his prediction in a complicated

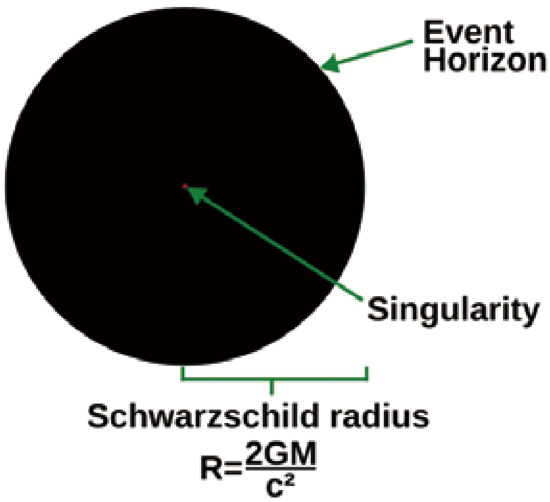


Illustration of a non-spinning black hole as predicted by Albert Einstein in his theory of general relativity. (Image by Sandstorm de - CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=74124922)

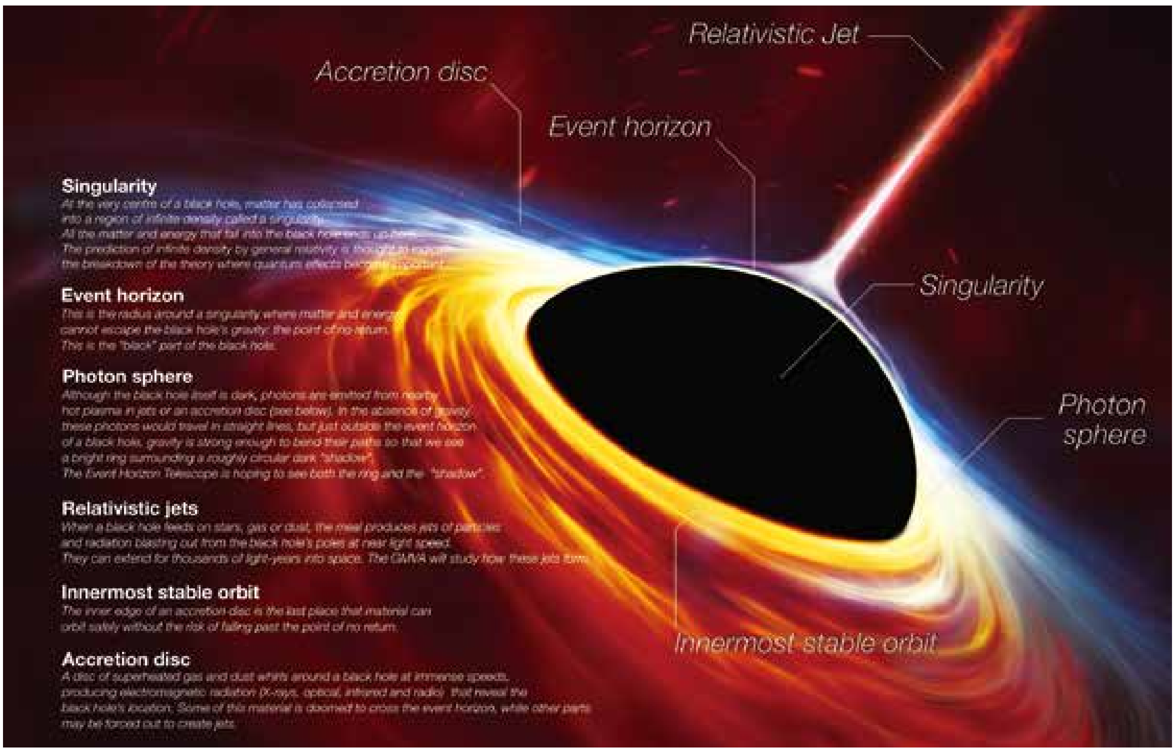
equation. To this equation German astronomer Karl Schwarzschild gave the first accurate solution in the next year, defining the boundary of EH for an object with a certain mass. The radius of this spherical space has since been called "Schwarzschild radius." The black hole's "shadow" has been predicted to look like a ring of light produced by the matter circling on the very edge of EH. The radius of this ring has been given as about 2.6 times of the Schwarzschild radius for a non-spinning black hole.

Whether this shadow exists, however, had been at dispute. Its existence had been "proven" by accumulated evidence, including theoretical calculation/modeling, and also observations. No direct evidence had been found, unfortunately, until we ultimately "beheld" a black hole afar at the heart of M87, thanks to EHT.

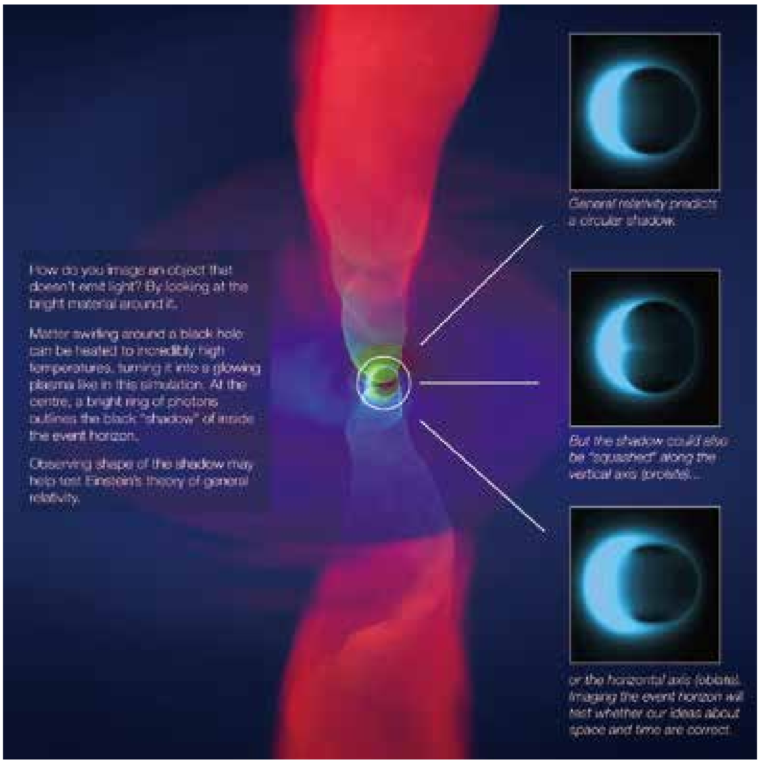
"All the observed characteristics of M87 black hole are in consistence with Einstein's prediction given a century ago about a spinning black hole," said Prof. LU Rusen, who participated in the EHT project, in a presentation given at the Shanghai release.

Powerful Existence, Tiny Size

Astronomers had been thinking about taking photos for black holes since decades ago. Yes, black holes are (at least hypothetically) dark, but the matter surrounding them are "bright" – it keeps emitting radio waves when falling prey of these formidable cosmic monsters, lighting up the predators with its last rays.



Black holes do not emit light; but the matter they are swallowing does. Any matter falling into the reach of its powerful gravity – the black hole shadow – would drop on it. The accretion disc revolves around the black hole at a speed close to light, and emits strong radio waves due to its hot temperatures. (Credit: ESO, ESA/Hubble, M. Kornmesser/N. Bartmann)



This infographic shows a simulation of the outflow (bright red) from a black hole and the accretion disk around it, with simulated images of the three potential shapes of the event horizon's shadow. (Credit: ESO/N. Bartmann/A. Broderick/C.K. Chan/D. Psaltis/F. Ozel)

Black holes are hungry for mass – They feed on gases or dust flying on the brim or within their shadows. Dropping onto the predator, the victims get accelerated by the latter's formidable gravity, and gradually gain their momentum to approach a velocity close to the speed of light. In the process, the matter is transformed into plasma state, heated to extremely high temperatures, and emits strong signals at different wavelengths, ranging from gamma rays to microwaves. This radio radiation can be picked up by radio telescopes – Thanks to the prey and the voracious gravity of black holes, human beings might be able to "see" these dark objects.

This demands an extremely big telescope, however.

Powerful enough, black holes are extremely tiny, compared to their enormous mass. Still, they are physically big for human beings, but the long distance between them and us makes them look extremely tiny from the Earth. Even under the lens of a powerful telescope, it is still invisible – Observing the supermassive black hole M87 from the Earth is just like shooting an apple on the Moon from the Earth.

What further add to the difficulty are the relatively longer wavelengths of the part of the radiation observable from the Earth. On their way to the Earth, parts of such emissions are absorbed by the interstellar matter, and some by the atmosphere of the Earth. Eventually the strongest radiation we can receive from the ground concentrates at wavelengths of around 1 mm. This is far longer than those of gamma rays and X-rays, and also those of visible lights – Visible lights have longer wavelengths compared to the former two, but the strongest signals from the black hole at M87 are in wavelengths at least over one thousand times longer than them. This means we need a much bigger telescope to capture such a tiny object at an acceptable resolution.

The resolution of a camera depends on the wavelengths of the radiation it uses to produce the image (for example an ordinary camera uses visible lights), and meanwhile the aperture of the lens. The shorter the wavelengths, and the larger the lens, the better a resolution we can achieve.

To obtain a clear photo of the black hole using the 1 mm microwave, we need a camera as big as the Earth.

A Camera as Big as the Earth

Can we really build such a gargantuan "camera?"

Yes. Thanks to a mature technology widely used in radio-astronomical observations called "Very Long Baseline Interferometry (VLBI)," this vision is not so out of reach. Actually, in the year of 2007, CAS used its own VLBI network to help accurately detect and monitor the loci of *Chang'e*-1, China's first lunar orbiter, when she was flying her maiden voyage to the Moon.

This technique connects radio telescopes together to form an array, in which every single telescope can work as an antenna to receive signals from the same target, and the whole array can work as an integrated big telescope, if the observational data can be combined and synthesized in a special way. In this case, radio waves from the same target arriving at different antennas in the array can be seen as signals arriving at two different points distributed apart on the same "dish" of a virtual telescope. The long distance between antennas (or the baseline) could be seen as a "chord" of the parabola surface of the virtual telescope – whose aperture depends on the longest distance between the antennas in the array, and whose imaging quality or fidelity depends on the number of baselines in the array. Just to think, if the distance between the antennas (or the baselines) can be extended to as long as the diameter of the Earth, we can claim that a virtual camera as big as the Earth is built.

Astronomers have been conceiving a global project to build such a camera for about two decades. This ambition was frustrated by the facilities available in the 20th century, however. The requested resolution and sensitivity pose many unprecedented challenges on the VLBI network. For example, working in sub-millimeter wavelengths requires an almost impossible surface accuracy of the antennas – it allows a deviation of no more than 50 microns away from the theoretically perfect surface, generally parabola. This is really demanding for large-aperture radio telescopes. Besides, working at these wavelengths, the system has to eliminate/bypass the influence from the water vapor in the atmosphere as much as possible, as the radiation from the target would be scattered by the tiny droplets in the air. On the other hand, connecting different antennas across continents and synchronizing the data from them are also an intimidating mission.

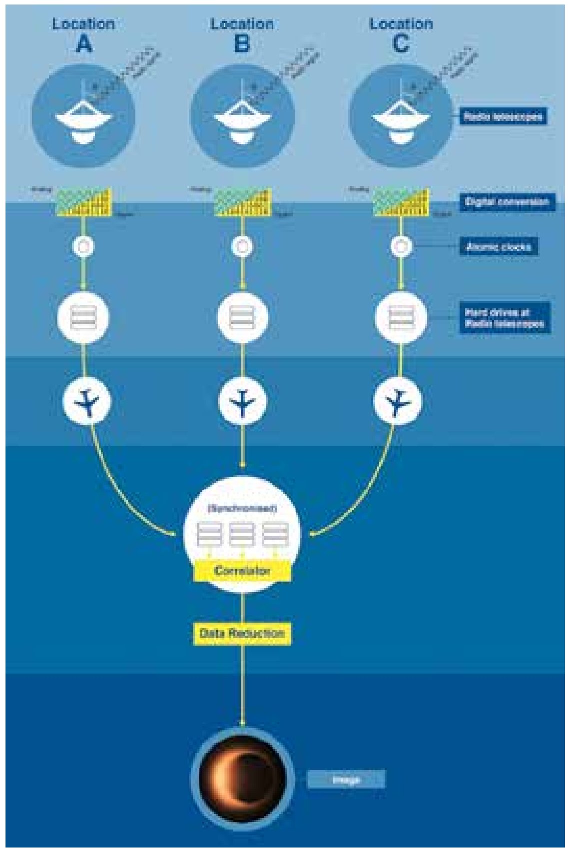
Latest developments in observational technologies and subsequently improved accuracy of telescopes, innovative algorithms, and smart connection of the best telescopes in the world have made it possible for scientists to make the dream come true.

One might be curious how the member telescopes in EHT talk with each other. After all, they are not physically connected with each other, whilst synchronizing the data from them is of great importance when working as ONE – Unless it would be impossible for the whole virtual telescope to "focus," and hence impossible to produce clear images of the target object. How should we "connect" them together to form an integral instrument?

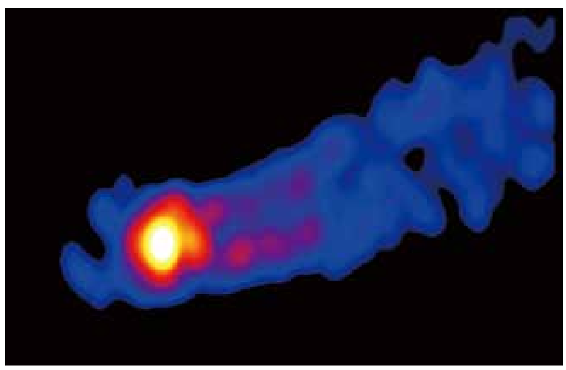
To solve this problem, scientists synchronize the antennas in the array via atomic clocks – as long as we know the accurate time at which signals from the same target arrive at the antennas, whose accurate locations are known, we can combine the data correctly, even if the antennas are not physically connected together. With a kind of special atomic clocks that are extremely accurate, scientists can eventually make this happen.

At last, seven radio telescopes of the EHT joined in the project to image the black hole at M87, working at a wavelength of 1.3 mm. VLBI technology allows the virtual "camera" to achieve an angular resolution of 20 micro-arcseconds – sharp enough to read a newspaper in New York from a sidewalk café in Paris, according to the news release.

The observation occurred in early April 2017, in 4 days during the period from April 5 to 14. The raw data produced from the observation mounted to 32 Gb a second, accumulating to petabytes a day. This unimaginable volume made it impossible to transmit the data through the Internet. The data produced by each telescope had to be stored on hard drives on the site along with time signals provided by the atomic clock, and shipped later to a central location for subsequent processing. Two supercomputers respectively hosted by the Max Planck Institute for Radio Astronomy (MPIfR) and the MIT Haystack Observatory are responsible for the data processing. CAS scientists



A schematic illustration for the VLBI observation which finally imaged the black hole. Each member telescope in the network is equipped with an extremely precise atomic clock, to keep them synchronized. The volume of data from the observation was too massive to transmit through the Internet, therefore the data was stored on hard drives on the site along with the time signals provided by the atomic clock. The hard drives are then shipped to a central location for processing. (Credit: ALMA (ESO/NAOJ/NRAO), J. Pinto & N. Lira.)



The EAVN image of M87 at 7 mm. (Credit: EAVN)

Simulated images of the shadow of a black hole: General relativity predicts that the shadow should be circular (middle), but a black hole could potentially also have a prolate (left) or oblate (right) shadow. Now the EHT image confirmed that the prediction Einstein gave over 100 years ago was right. (Credit: D. Psaltis and A. Broderick)

participated in the data processing at MPIfR, and some contributed to the theoretical modeling of the data.

The seven telescopes contributing to the published results are: ALMA, APEX, the IRAM 30-meter telescope, the James Clerk Maxwell Telescope (JCMT), the Large Millimeter Telescope Alfonso Serrano, the Submillimeter Array, and the Submillimeter Telescope. CAS helped operate JCMT in Hawaii and participated in its observation.

Notably, during the EHT campaign observation in April 2017, astronomers from China, Japan and Korea conducted a serial of dense observations of M87 black hole at the wavelengths of 7 mm and 1.35cm, using the East Asia VLBI Network (EAVN) – a VLBI network combining radio telescopes from the three countries. This EAVN observation set constraints of some important parameters for the EHT observations of M87.

Endless Quest

It took the EHT team two years to "develop" the "plate." After complicated calibration and calculation, two independent processing teams confirmed that EHT had successfully captured the shadow of the black hole at M87.

"The successful imaging of the black hole at the center of M87 is just the beginning of the EHT collaboration," commented Prof. SHEN. "We are expecting more exciting results from the EHT project in the near future."

"We have achieved something presumed to be impossible just a generation ago," concluded Doeleman, the EHT project director. "Breakthroughs in technology, connections between the world's best radio observatories, and innovative algorithms all came together to open an entirely new window on black holes and the event horizon."

Prof. XUE Suijian, vice director of NAOC echoed their vision. "Yes, now we know what a black hole shadow looks like," he said, "but we still do not know exactly what is in the shadow – we have no idea what kind of matter it is, nor do we know its detail structure. This deserves continued exploration, and I am confident that human beings will unveil this mystery one day."