Newsletter Interview

THE IMAGE OF SGR A*, THE DARK HEART OF THE MILKY WAY, UNVEILED

Interview with Marifelicia De Laurentis, professor at the University Federico II in Naples, researcher at the Naples INFN Division and Ciriaco Goddi, professor at the University of Cagliari and researcher at the Cagliari INFN and INAF divisions.

Beyond its unquestionable scientific value, the first and striking image of Sgr A*, the supermassive black hole at the heart of our galaxy, presented on 12 May by the Event Horizon Telescope (EHT) international collaboration at three simultaneous press conferences held in Europe, Asia and the USA, is an emblematic case of technological success. While the possibility of observing the swirling behaviour of matter around the event horizon of a black hole made it possible to test the predictions of Einstein's general relativity in a so-called strong gravitational field, access to this information required the adoption of data acquisition and integration techniques and systems capable of overcoming the experimental difficulties associated with the distance separating Sgr A* from our planet, which is approximately 27,000 light years away, and the extremely variable nature of this particular black hole. Hurdles which were overcome by creating a virtual telescope the size of Earth, using the network of eight radio-astronomical observatories, distributed around the globe, which make up the EHT. A solution that has already proven to be successful with the production and revelation of the first "photo" of a black hole, M87*, in 2019.

The technological connotation of Sgr A*'s image enhances the scientific importance of the result, which has provided new and decisive evidence for the existence of a compact black body at the centre of the Milky Way, providing a new test bench for General Relativity and for the study of the behaviour of space-time in otherwise unfathomable contexts, as also demonstrated by the publication, simultaneous to the announcement on 12 May, of the six papers signed by the scientists of the EHT collaboration, including Mariafelicia De Laurentis, professor at the Federico II University in Naples, researcher at the INFN division in Naples and co-ordinator of one of the papers published in The Astrophysical Journal Letters, and Ciriaco Goddi, professor at the University of Cagliari and researcher at the INFN section in Cagliari and INAF.

MARIAFELICIA DE LAURENTIS

The main objective of the EHT collaboration has always been to acquire an image of SgrA*. When did the hypothesis concerning the presence of a compact celestial body at the centre of our galaxy mature and what kind of evidence existed, prior to the result obtained by EHT, for its existence?

The approximate position of Sagittarius A* in the centre of the Milky Way has been known for almost a century. It was first found by monitoring the positions and velocities of globular clusters, which tended to orbit around a common point. However, the telescopes of the past were not able to detect any interesting objects due to the presence of dust, in the central regions of our galaxy, which is so dense that it is able to extinguish almost all forms of light coming from the galactic centre. An obstacle that only radio signals can overcome. Therefore, only in 1933, thanks to the invention of radio telescopes and to the pioneering work of Karl Jansky, it was possible to identify a surprisingly bright source of radio waves coming from the Sagittarius constellation, which was immediately associated with the galaxy's centre. However, it was the advent of radio interferometry, starting in the '70s, that allowed more information about Sagittarius A* to be collected. With clearer and more detailed observations, it was indeed possible to start making estimates on the size and mass of the object emitting such a high flux of radio waves, discovering that it was both smaller than our solar system and millions of times more massive than the Sun. Characteristics that are only compatible with a supermassive black hole. Subsequent technological advances then allowed us to obtain very high precision observations, by tracking individual stars as they orbited around Sagittarius A* at a speed just a fraction below the speed of light. These observations were crucial as the stars orbit around the supermassive black hole quickly. By carefully observing them over years and even decades, it has been possible to deduce the properties of gravity in this extreme environment, providing an instrumental test of Einstein's theory of general relativity. These fast stars also serve to clearly demonstrate that Sagittarius A* is indeed a black hole, as other arrangements such as a dense cluster of dead stars would produce different orbits.

What are the main characteristics of the image and what kind of information can be derived from its observation on the properties of Sgr A* and the region of space surrounding it?

The picture shows exactly what we would expect to see around a supermassive black hole that, as such, does not emit any light of its own. The bright halo visible in the picture is in fact produced by the gas and dust surrounding Sgr A*. At the centre of the ring is a dark region called the shadow, which contains the event horizon of the black hole, the surface beyond which nothing, not even light, can escape the black hole. The outer material, moving rapidly and compressing on its way to the event horizon, can reach temperatures of up to 10 million degrees Celsius. At these temperatures, the material, which rapidly forms a thin, rapidly rotating accretion disk, emits intense amounts of radiation across the entire electromagnetic spectrum. Most of that radiation is absorbed by the gas and dust within the galactic core, with only X-rays and radio emissions making their way through the galaxy to our planet.

Why are we certain that the one observed by the EHT collaboration is indeed a black hole?

What makes us confident about the nature of the observed object are the equations of General Relativity, whose predictions are reflected in the image of Sgr A*. Indeed, among the solutions of Einstein's theory are those that describe extreme gravitational phenomena, called singularities, in which the curvature of space-time produced by an extremely compact body is such that even light cannot escape. The first contribution in this direction was in 1916 by Karl Schwarzschild, whose solution, although initially regarded as a mere mathematical result, without an actual astrophysical counterpart, was able to provide indications of the size of the event horizon of an object with spherical and static symmetry. It was then Roy Kerr, in 1973, who extended the validity of Schwarzschild's result to real contexts involving rotating black holes, through the development of a suitable metric. It is thanks to such solutions that, starting from the mass, it was possible to establish an estimate for the radius of Sgr A*'s event horizon. This prediction was confirmed by the EHT observations, thus producing yet another confirmation of General Relativity, even in a strong gravitational field such as the one dominating the galactic centre.

What are the similarities and differences between Sgr A* and M87?

The results of these new measurements of Sgr A* provide further evidence that astrophysical black holes, regardless of their mass and differences, are described by solutions of Einstein's theory. M87* boasts a mass of 6 billion suns and is gigantic in size. Our entire solar system would fit within its event horizon. In contrast, Sgr A*, which is only 27,000 light years from Earth, is relatively small in size. With "only" 4 million solar masses, it is small enough to fit into the orbit of Mercury, the closest planet to the Sun. If the two black holes were lined up for a photo shoot, M87* would fill the frame, while Sgr A* would disappear altogether. Moreover, while M87* voraciously devours surrounding matter, perhaps entire stars, and emits a jet of energetic particles that illuminates its galaxy, Sgr A*'s appetite, by comparison, is minimal. Nevertheless, the two bodies, due to the distance separating them from Earth, appear more or less the same size in the sky, as predicted by Einstein's theory of gravity, according to which the image of a black hole varies only as its mass varies: a black hole 1,000 times smaller in mass than another will have a very similar image, only 1,000 times smaller. The same is not true for other objects. Ultimately, the size of these celestial bodies does not affect their appearance, as they only respond to one law of nature: gravity.

CIRIACO GODDI

What are the main difficulties one faces when acquiring and processing images of M87 and Sgr A*?

Radio telescopes, instruments that pick up the electromagnetic signal in the radio wave spectrum, were used to create the image of Sgr A*. The photo thus represents a map of the light emitted by the incandescent plasma orbiting the black hole just before it plunges into the event horizon. One of the main difficulties in capturing an image of a black hole is the size of these objects, which are very small, because their main characteristic is that they concentrate a huge amount of mass in a small volume. To put this into perspective, it is as if the entire mass of the Sun was concentrated in an object with a diameter of just over a kilometre. If, on the other hand, we consider the largest black holes we know of, such as Sgr A* and M87*, which cover greater angles in the sky, their size corresponds to a doughnut on the Moon seen from Earth. There is hence no optical telescope with such a high resolution power to enable us to distinguish such objects. We would need an instrument with a mirror of several kilometres, which we cannot build with current technology. Apart from these difficulties, we prefer to make use of radio waves rather than visible light to observe black holes because they allow us to penetrate the blanket of clouds and gas that envelops our galactic centre by totally obscuring it in visible light. This aspect complicates the ability to observe black holes even more because, for the same size, the resolution of telescopes worsens as the wavelengths of the signals of interest increase. Specifically, to build a radio observatory with the necessary capabilities for our purposes, we would have to build an antenna 10,000 kilometres in diameter, i.e. a dish with the size of earth's circumference.

What kind of solution was adopted to overcome these experimental and technological limitations?

Although it is not possible to make an Earth-sized telescope, it is nevertheless possible to simulate it and replicate its performance behaviour. This is what was done by the EHT collaboration, by adopting a technique called Very Long Baseline Interferometry (VLBI). This solution employs a global network of radio telescopes, located on different continents, that observe the same source together at the same time. The radio telescopes work in pairs, and each pair receives radio waves from the source with a delay of one millionth of a second each, a difference measured by precise atomic clocks, which allows us to synchronise the radio waves. Together with this temporal precision, the distance between observation sites finally allows us to obtain spatial information about the source: the greater is the distance between radio telescopes, the smaller is the size of the object you can observe. For this technique to work, you need a minimum number of telescopes positioned in strategic areas of the globe, which has to be covered as uniformly as possible. The telescopes must also be installed in sites with a dry climate and high altitude, such as the Atacama Desert in Chile, because the main enemy of radio telescopes is water vapour, which tends to destroy the high frequency radio signals. These were the challenges faced by EHT, that now has a network of 10 radio telescopes.

How does the processing of acquired data take place?

There are many technical details behind the processing of the data from which the images are produced, and they relate to the three fundamental steps into which the EHT collaboration's work is divided. The first step concerns data correlation: the signals picked up by the different antennas are digitised and sent to two correlation centres, one in Europe, at the Max Planck Institute for Radio Astronomy in Bonn, and the other at the Massachusetts Institute of Technology, where two supercomputers combine the data. Amounting to several petabytes, the total volume of data acquired in each observation campaign is recorded on several tons of hard disks. Once the correlation is complete, we move on to calibration, which is carried out by a working group of scientists from all over the world, in order to measure the astronomical signals in the data after wiping them from instrumental and atmospheric noise. Several strategies were adopted to ensure the consistency and reliability of this work, which is subject to the personal choices made by the scientists, by distributing it to different teams and by adopting different algorithms. Finally, the last step is dedicated to imaging, which allows the reconstruction of the astronomical image of the source through the use of software. Again, in order to avoid personal bias, the work is carried out by independent teams. It took five years to process the Sgr A* image, i.e., three years longer than for M87*, due to the extreme variability of the black hole at the heart of the Milky Way, that greatly complicates the data analysis.

What will the EHT collaboration's next goals be?

The next goals of the EHT collaboration expect the inclusion of more telescopes to improve image quality. Having more observatories, evenly distributed in different parts of the globe, will allow us to observe even more details and fine structures of the sources. This is not because it will increase the resolution of the images, which are constrained by the size of Earth's diameter, but because a larger sampling will allow us to reconstruct photos with higher fidelity. We are therefore already working on a new network of next-generation telescopes, which will include many more sites both in the Americas and Europe, and in Africa, where there are currently no radio telescopes in the EHT network. We are also focusing on observations in higher frequencies, which allow us to achieve better angular resolutions, even when using the telescopes themselves. However, the insurmountable constraint here is our atmosphere, which becomes an even more limiting and variable factor as the frequencies captured increase. For this reason, the next frontier of the EHT collaboration will become space, where, in addition to solving the problem of atmospheric distortion of the signals, we would have no obstacles related to the visibility of the source: the exposure of the various terrestrial radio telescopes currently has a useful observation window of only a few hours per night due to the rotation of the planet. Observational campaigns carried out by space-based observatories would therefore allow us to create real films of the plasma orbiting Sgr A* and M87* and to capture images of other black holes at the centre of other galaxies.