Technologies and Principles Indicated in The Black Hole Image

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Abstract. On April 10, 2019, Event Horizon Telescope (EHT) released the first image of a black hole in the M87 galaxy [3]. This picture became popular on the Internet all over the world and a great number of people started to discuss it. However, many of them could not understand the scientific meaning of this picture and the laborious process to capture this image. Therefore, this paper is going to explain the works and results of EHT to non-physicists. This paper is separated into two parts, including the technologies and principles that are indicated in the black hole image. Technologies include very long baseline interferometry (VLBI), which is used to increase the details of the image and the general-relativistic magnetohydrodynamics (GRMHD) simulation used to simulate different black hole models. The principles contain Kerr’s model, which is the main model used in EHT’s research and Doppler effect. This research also discussed that the image of the black hole is similar to the Kerr’s model. However, some alternatives of the the Kerr model are different from the actual data.

1. Introduction
Scientists used plenty of methods to detect black holes but no one had taken an image of them until 2019, when Event Horizon Telescope (EHT) captured the first image of the black hole in the M87 galaxy. But the majority of people who discuss it on the internet do not know the meaning of the image mean or the measures that scientists capture this image. This paper is going to discuss the technologies and principles indicated in the black hole picture, in order to allow more non-physicists to understand the significance of this work.

EHT is an international organization, which was established in 2009, to detect black holes, and it has created a global network of radio telescopes. EHT successfully took image of the structure of the black hole in the M87 galaxy. The structure is like a light ring around the dark centre of the black hole with greater brightness at its south part. M87 galaxy is giant and has an elliptical shape. This galaxy contains a supermassive black hole and trillions of stars, which are much more than the stars in our Milky Way galaxy, containing only several hundred billion stars. M87 galaxy is about 54 million light-years away from the earth [1], and the black hole in it has mass \( M = (6.5 \pm 0.7) \times 10^9 M_\odot \), where \( M_\odot \) is the solar mass (=1.989 × 10^30 kg). The diameter of the bright ring is 42 ± 3 μas. In addition, the ring structure also has a central brightness depression contrast ratio > 10:1, which is the reason why people can observe and distinguish the ring and the shadow inside it [5].

2. Models
A black hole has an enormous mass, therefore it can cause the utmost curvature of spacetime. This curvature of spacetime is described by Einstein’s field equations (EFE) of general relativity in 1915,
The Einstein field equations (EFE) describe the distribution of mass and energy in the spacetime, \( G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} \) (1)

where \( G_{\mu\nu} \) is the Einstein tensor, \( \Lambda \) is the cosmological constant, \( g_{\mu\nu} \) is the metric tensor and \( T_{\mu\nu} \) is the stress-energy tensor. A tensor can be seen as the properties of an object that transforms in certain rules due to the change of the coordinates and these rules do not vary in different coordinates of the spacetime. That is the reason that tensors are used in EFE, which contains the variation of spacetime. In EFE, \( T_{\mu\nu} \) describes the distribution of mass and energy in the spacetime, \( G_{\mu\nu} \) contains information about the curvature of the spacetime and \( g_{\mu\nu} \) is a measurement of the shape of the spacetime. Combining all these tensors, the EFE describes how mass and energy can cause the wrap of the spacetime and what is the distribution of mass and energy in the spacetime.

Due to the curvature of spacetime, anything even light cannot escape from black holes. Because of this feature, black holes are hard to be observed. But scientists still successfully use gravitational waves and X-rays to prove the existence of black holes. A black hole has an event horizon that the substances move once passing through this horizon, can never escape from it. Outside of the event horizon, there is a photon sphere, where the gravity at this place is very strong, causing light or photon particles to circularly orbit the black hole. The innermost centre of the black hole is the singularity where matter is compressed to an infinitely small point.

There are many models about black holes, being solutions of this Einstein field equations. One of these models is the Schwarzschild metric describing non-rotating black holes. In this model, the electric charge, angular momentum and the universal cosmological constant of the black holes are assumed to be zero. The radius of the event horizon can be predicted in Schwarzschild metric that,

\[ R_s = \frac{2GM}{c^2} \] (2)

where \( R_s \) is the Schwarzschild radius (event horizon radius of a non-rotating black hole), \( G \) is the gravitational constant, \( M \) is the mass of a black hole or any other object, and \( c \) is the light speed. Some of the photons, moving into the black hole, rotate around the black hole and form the photon sphere, while some of them pass through the event horizon and are absorbed by the black hole. Whether the photons are absorbed or not depends on the impact parameter of the photons and the photon capture radius of the black hole. Impact parameter is the perpendicular distance between the projection path of an object and the centre of a potential field around it. The photon capture radius equals,

\[ R_g = \sqrt{2Mr_g} \] (3)

where \( r_g = \frac{1}{2}R_s = \frac{GM}{c^2} \). If a photon has an impact parameter smaller than \( R_g \), this photon should pass through the event horizon and be captured by the black hole. Oppositely, when the impact parameter is greater than \( R_g \), the photons should orbit the black hole and become a part of the photon sphere. Schwarzschild’s black holes only describe the non-rotating, perfectly spherical black hole, thereby only a perfectly spherical object can collapse to this kind of black hole [2]. However, objects in real life, such as the earth, are not perfect sphere which cannot form a Schwarzschild’s black hole. Then another model appeared, which named the Kerr model. Kerr model describes an uncharged black hole rotating at a constant rate, so the size and shape of this black hole only depend on its mass and angular momentum [2]. This kind of black hole contains an ergosphere, which is an ellipsoidal region between the event horizon and the photon sphere. Therefore, the structure is that the outermost layer is the photon sphere and the middle layer is the ergosphere. Then is the event horizon while singularity is at the centre of the black hole.

The Kerr model is the main model used in EHT research of M87 black hole and one of the hypotheses of this research is to prove that whether the Kerr model is consistent in the M87 Blackhole.

3. Technologies
EHT created a global network of different radio telescopes, which is shown in figure 1. The eight telescopes in this network are ALMA (Atacama Large Millimetre/submillimetre Array) and APEX (the
Atacama Pathfinder Experiment telescope) in Chile, LMT (the Large Millimetre Telescope Alfonso Serrano) in Mexico, PV (the IRAM 30 m telescope on Pico Veleta) in Spain, SMT (the Submillimetre Telescope Observatory) in Arizona, JCMT (the James Clerk Maxwell Telescope) and SMA (the Submillimetre Array) in Hawai‘i, and SPT (the South Pole Telescope) in Antarctica [5].

![Figure 1. The global network of radio telescopes in EHT. There is a total of eight telescopes in 6 different locations [5].](image)

The reason for using so many telescopes was to increase the angular resolution. Angular resolution is the smallest angular separation between two points that are needed to distinguish them. Hence, smaller angular resolution means less angular separation are needed to resolve two points seen by the telescopes. Smaller angular resolution means the image can contain more details and show the object on it more clearly. The calculation of angular resolution is that,

\[ R = \frac{\lambda}{D} \]

where \( R \) is the angular resolution, \( \lambda \) is the wavelength of light and \( D \) is the diameter of the telescope.

The black hole in the M87 galaxy is far from the earth, so very small angular resolution is needed to increase the details of the image. The two ways to decrease the angular resolution are decreasing the wavelength of detected waves and increasing the diameter of telescopes. The shortest wavelength of radio waves that passes through the atmosphere and reaches radio telescopes is 1.3 mm, which cannot be any smaller. In this smallest wavelength, the angular resolution is still not small enough to observe the black hole. Thus, EHT started the very long baseline interferometry (VLBI) program [7]. When there are two telescopes with a diameter of 10 m, 1000 m apart from each other, the diameter can be seen as a large telescope with a diameter of 1000 m by combining the received waves of each telescope, and this combining diameter is called the baseline. VLBI is to create an earth-sized network of telescopes so that the diameter of the “telescope” can be seen as the diameter of the earth. This program succeeded, that EHT used eight radio telescopes at six different geographical positions and the baselines of these telescopes are in the range of 160 m to 10,700 km. Then, the angular resolution becomes very small which is around 25 μas and it is just enough to take a clear image of the M87 black hole.
The technique to combine the data of two or more telescopes is called interferometry. When two telescopes at different locations record the same signal, the recorded waves of two telescopes have a phase difference, and this difference changes when the direction of the signal changes. Hence, scientists can measure the phase difference of identical waves recorded by different telescopes, and then use this wave difference to find out the direction that the signal comes from. Next, scientists can combine the waves from different directions, thereby creating the image of the wave strength of the black hole in the M87 galaxy. This image is shown below.

![Figure 2. Image of black in M87 galaxy. The brighter area means larger radio wave strength [5].](image)

4. Principles

EHT created a geometric and general-relativistic magnetohydrodynamics (GRMHD) model of the Kerr metric. This model depends on two parameters, which are dimensionless spin $a^*$ and the net dimensionless magnetic flux over the event horizon $\varphi$. The equations of these two parameters are,

$$a^* = \frac{Jc}{GM^2}$$  \hspace{1cm} \text{(5)}

where $J$ is the spin angular momentum, $M$ is the mass of the black hole and $G$ is the gravitational constant [5].

$$\varphi = \frac{\Phi}{M^2 R_g}$$  \hspace{1cm} \text{(6)}

where $\Phi$ is the magnetic flux and $\dot{M}$ is the mass flux across the event horizon [5].

These two parameters were used to simulate different situations of the accretion disk. The accretion disk is formed by materials orbiting the black hole spirally. When $a^* \geq 0$, the accretion disk is prograde; and when $a^* < 0$, the accretion disk is retrograde corresponding to the spin axis of the black hole. If $\varphi$ is about 1, the accretion flows are in Standard and Normal Evolution (SANE). If $\varphi$ is about 15, the accretion flows are in Magnetically Arrested Disk (MAD).

The image of the black hole captured by EHT shows that the black hole has a magnetized accretion flow orbiting the event horizon, which is consistent with the Kerr’s black hole model. All of the accretion models are consistent with this image, except for $a^* = -0.94$ MAD models, which fail to produce images that the variance among snapshots is too large to be consistent with the observed image.

The observed black hole has a bright circular ring around a dark area in the centre in figure 2. This bright ring is the photon sphere that waves are emitted from the hot plasma surrounding the black hole and these waves orbit the black hole due to the massive gravitational lensing. The radius of the photon ring is predicted by the equation:

$$\theta_p = \frac{\sqrt{2GM}}{c^2D} = 18.8\left(\frac{M}{6.2 \times 10^9 M_\odot}\right)^{-1}\left(\frac{D}{1.69 M_p c}\right)^{-1}$$  \hspace{1cm} \text{(7)}

4
where $M =$ mass of the black, $D =$ the distance from the black hole to the earth, and $\theta_p$ is the photon angular radius [6]. The prediction of the radius is about 18.8 $\mu$as, which is similar to the detection of the M87 black hole with an angular radius of about 21 $\mu$as. Therefore, this result can prove that the prediction of emission of waves is caused by the hot plasma surrounding the black hole and the strong gravitational field.

The accretion rate of the black hole can be calculated through the following equation,

$$
\dot{M} = 4\pi r^2 \rho v^7
$$

$$
\approx 4\pi (5g)^2 n_e m_p (c/\sqrt{r})
$$

$$
\approx 2.7 \times 10^{-3} M_\odot \text{yr}^{-1}
$$

where $r$ is the Kerr-Schild radius and $r \approx 5g$, $n_e$ is the electron number density and $m_p$ is the mass of photon [6].

Thus, the Eddington accretion rate equals to,

$$
\dot{M}_{\text{Edd}} = \frac{L_{\text{Edd}}}{c^2} = \frac{2.2}{\epsilon} \left( \frac{M}{10^9 M_\odot} \right) M_\odot \text{yr}^{-1}
$$

where $L_{\text{Edd}}$ is the Eddington Luminosity and $\dot{M}_{\text{Edd}}$ equals 137 $M_\odot \text{yr}^{-1}$[7]. Hence, $\dot{M}/\dot{M}_{\text{Edd}} \approx 2.0 \times 10^{-5}$[6]. This is similar to the results that the mean ratio of two accretion rates is about $10^{-6}$ in MAD models. When $a^*$ is smaller than 0, the ratio is about $5 \times 10^{-5}$ in SANE models. When $a^*$ is smaller than 0, the ratio is about $2 \times 10^{-4}$ in SANE models.

The ring is brighter at its south part than its north part because of the doppler effect of the waves and the source. Doppler effect illustrates that the observed wave is different wavelength or frequency from the actual wave, when the source is moving relative to the observer. The equation about this is shown below,

$$
f_{\text{observed}} = \frac{c \pm v_o}{c \pm v_s} f
$$

where $c$ is the speed of waves, $v_o$ is the speed of the source, $v_s$ is the speed of the observer, $f_{\text{observed}}$ is the observed frequency and $f$ is the actual frequency. When a source is moving towards a stationary observer, there is a $-v_s$ in the equation (6) and the $v_o$ is zero. Thus, the observed frequency becomes larger and the observed wavelength becomes smaller, as frequency is inversely proportional to wavelength. When the frequency becomes smaller, the energy of the wave becomes larger. As the brightness depends on the strength of the waves in EHT’s black hole picture (figure 2), the larger observed energy leads to the larger brightness on the image. Therefore, the brighter part of the photon ring in the image means that the substances (plasma) that emit waves, are moving towards the earth. This phenomenon also indicates that the plasma of the black hole is rotating clockwise, when being viewed from the direction of its movement, which is the right side of figure 2. Furthermore, this north-south asymmetry is consistent with models that the spin of the black hole is pointing away from the earth, and is inconsistent with the models where the spin points toward the earth.

In addition to the Kerr model, EHT also tested other models, such as the models of black holes that include additional fields. These models contain black holes with electromagnetic, regular black holes in nonlinear electrodynamics, black hole metrics affected by a cosmological constant, etc. The structures of these models are similar to Kerr’s model and researchers cannot prove it to be wrong in recent observations and data. However, the most extreme examples about that black holes are surrounded by massive scalar fields, which were very different from the observations. There are no additional lobes in the shadow, which is predicted by these examples, in the M87 black hole [4].

5. Conclusion

EHT organized eight radio telescopes in six different locations in order to get a very long baseline interferometry (VLBI) system. As the smallest wavelength of radio wave reaches the telescopes from the outside of the earth is 1.3mm, the only way to further decrease the angular resolution of the image is to increase the baseline of the telescopes. The decrease of angular resolution can increase the details of the image so that the M87 black hole, which is very far from the earth, can be observed. The main model used in EHT’s research is the Kerr’s model, which assumes a black hole without charge and
rotating at a constant rate. To compare the actual black hole to this model, GRMHD simulation was used and the two parameters of it, which are the dimensionless spin $a^*$ and the net dimensionless magnetic flux $\phi$ over the horizon are analyzed. EHT compared different parts of the model to the actual black hole, such as the radius, asymmetry, and the brightness contrast of the ring.

Hence, the conclusion could be drawn that the data are similar to Kerr’s black hole model in many aspects such as the radius, asymmetry of the photon ring and the spin direction of the accretion disk. However, some alternatives of Kerr’s model are proved to be inconsistent with the real data, such as the structure of a massive scalar field surrounding black holes. Many details of EHT’s research are not included in this paper to make non-physicists easily understand. The whole details can be found in the papers released by EHT [5,6]. In the future, the author will keep on conducting research like how astronomers found out the structure of a black hole, in order to have a much deeper understanding of this field.

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