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The main aspects of black hole theory

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Abstract. Black holes are extremely compact objects which no one knows exactly what it is, and astrophysicists, whether in the past or the present, have been devoting a great deal of time to studying them. The establishment of black hole theory takes a lot of time. There are quite some difficulties in breaking continuous negation, admitting, and researching black holes. In this paper, we first look back at the discovery process of black hole theory. We mainly review the three aspects of black holes: physical properties, classification and observational methods. Black holes are invisible and many astrophysicists in the past only can investigate them based on theoretical understanding, so we present some new and clear evidences of black holes to prove this theory. In this paper, some new models and applications of black holes (e. g. Hawking Radiation Theory, The Penrose Process) that may be discovered in the future will be presented too.

Keywords: Black holes, No Hair Theorem, Event horizon, Black holes detection, Hawking Radiation.

1. Introduction

As the motto goes, “All truths grow in three stages. First, they are exposed to relentless ridicule, then they suffer fierce opposition, and finally, they are gladly accepted as a matter of course.” Black hole physics is undoubtedly the best description of this statement. John Michell and Pierre-Simon Laplace first discussed the possibility of highly compact objects in the background of neoclassical mechanics at the end of the 18th century. They found that the strong gravitational field of such objects could prevent light from escaping through Newtonian formulas. In 1915, Albert Einstein proposed the theory of general relativity, in which he predicted that certain massive stars would eventually evolve into dense objects such as black holes. In 1916, the German astronomer Karl Schwarzschild found that if the actual radius of a celestial body was less than a particular value, then an edge (which we call an event horizon now) could be found around the celestial body. Once entering this edge, no object could escape out of it, even light. This particular value became known as the Schwarzschild radius. In 1939, the classic paper by Oppenheimer and Snyder first introduced this phenomenon. They found that the sphere would eventually be cut off from all contact with the rest of the universe, which was consistent with what astronomers had previously discovered. However, Einstein himself claimed that we do not have to worry about the possibility of this happening because no matter could ever be compressed to such a radius. Moreover, his mistake was that he only considered objects in equilibrium. Even the cool-headed Landau was troubled by this prospect, and in an attempt to circumvent the problem, he argued that all stars heavier than 1.5 M must have regions that violate the laws of quantum mechanics. In 1967, the term black hole was formally introduced in a lecture given by John Archibald Wheeler. In 1970, the American

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satellite "Liberty" observed a binary star system in Cygnus: a star more than 30 times heavier than the Sun was being pulled by an unobserved object weighing about ten times the mass of the Sun. Astronomers surmised that this unseen object was a black hole, which was later confirmed to be a black hole, and it was the first black hole discovered by humanity. Throughout the development of black holes, one person who has made a remarkable contribution and must be mentioned is Stephen Hawking. He proved the area theorem of black holes. He also raised the black hole evaporation theory, the Hawking model of the unbounded Universe and Hawking radiation.

In the next few decades, astronomers have observed many black holes, which confirmed the existence of black holes. But a very realistic problem is in front of the astronomers. Because light cannot escape from the black holes, astronomers can only indirectly observe other celestial bodies to speculate the existence of black holes in some places. That is to say, we cannot see the true face of the black hole. Finally, in 2019, the Event Horizon Telescope (EHT) project team revealed a black hole's true face for the first time: a black hole in the Virgo A galaxy (M87). In 2022, the Event Horizon Telescope (EHT) Collaboration officially released the first pictures of Sagittarius A* (Sgr A*), the black hole at the centre of the Milky Way.

The primary purpose of writing this paper is to help people who are interested in or want to learn more about black hole physics, so the paper systematically reviews the knowledge related to black holes. This paper will summarize the knowledge of black holes so far and explore the conjectures and possibilities that black holes may have in the future.

2. The definition and character of black holes

2.1. *The origin of black holes*

Similar to the creation of neutron stars, when a star evolves to the point where it is about to collapse on itself, the core rapidly contracts and collapses under its own gravity. If a neutron star is formed, the contraction will stop as soon as all the material in the core becomes neutrons. However, a star that forms a black hole has a core with such a large mass that the repulsive force of the neutrons cannot prevent it from continuing to collapse. So the star collapses endlessly, and the "monster" formed at the end of this extreme process is a black hole. But if a star only left three or fewer times than the mass of the Sun, it will not form a black hole but a neutron star or supernova. This is the most classical model of black hole evolution.

2.2. *Definition of black holes*

Black holes are extreme celestial bodies with extremely high density in the universe, and their gravitational field is so large that all the matter (even light), once entering its inner space, cannot escape. Different from other celestial bodies, black holes are very unusual: People cannot observe them directly, and astronomers can only propose a variety of speculations on their internal structure because they cannot see it. Three "levels" of black holes are now delineated: the outer Event Horizon, the inner Event Horizon, and the Singularity. The Event Horizon of a black hole is the boundary of the black hole. Sometimes, when the matter is drawn into the black hole, it bounces off the Event Horizon and is thrown outwards instead of being caught in the black hole, which also creates bright jets at a very fast speed. Although we cannot see it directly, we can see these powerful jets even from a great distance. The black hole's singularity is a point in space-time where all the masses of black holes are compressed inside.

2.3. *Event horizon*

The limiting radius of a black hole is often referred to as the "event horizon," which is the frontier beyond which escape is impossible, even for light.

Starting from the Newtonian mechanics formula:

Based on Newton's second law:

$$F = ma \tag{1}$$

Also, based on the law of gravity:

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$$F = G\frac{Mm}{R^2} \tag{2}$$

On the surface of a celestial body, where the acceleration a can be equal to the gravitational acceleration g on the surface of the body, it can be introduced:

$$g = \frac{GM}{R^2} \tag{3}$$

Substituting:

$$E_g = mgh \tag{4}$$

Into:

$$g = \frac{GM}{R^2} \tag{5}$$

One derives:

$$E_g = \frac{GMmh}{R^2} \tag{6}$$

On the surface of a celestial body, h=R:

$$E_g = \frac{GMm}{R} \tag{7}$$

Let the kinetic energy of the object be:

$$E_k = \frac{1}{2}mv^2 \tag{8}$$

So the limit value of the object that cannot escape the gravitational pull of the celestial body is:

$$\frac{1}{2}mv^2 = \frac{GMm}{R} \tag{9}$$

Hence, Schwarzschild Radius [1] is derived:

$$R = \frac{2MG}{v^2} \tag{10}$$

We know that v equals c is the critical celestial radius at which light can't escape the gravitational pull of a celestial body exactly, hence:

$$R = \frac{2MG}{c^2} \tag{11}$$

Forming a black hole is not just based on the vast mass. If a star ends up with too much mass left behind, it will not form a black hole but a white dwarf or a neutron star, so we want a star to collapse into a black hole only when it satisfies this equation.

2.4. No Hair Theorem of Black Holes

The No Hair Theorem of Black Hole [2] is a conclusion proved by Hawking, B. Carter and other people in 1973 through mathematically rigorous calculations. It states that no matter what kind of black holes they are, their final properties are only determined by three physical quantities (mass, angular momentum and electric charge). In simple words, after the formation of a black hole, it will be dominated only by its mass, angular momentum and electric charge [3], and the black hole will not have the characteristics of other information or matter that makes up itself.

3. Mass classification of black holes

Based on General Relativity, there is no limit to the value of a black hole's mass (that is to say, the masses of black holes can be tiny but their density must be enormous), so astronomers classify black holes into three types based on their mass: stellar black holes (less than 100 times the mass of the Sun), Intermediate-mass black holes (100-100,000 times the mass of the Sun), and Supermassive black holes (100,000 times the mass of the Sun or more) [4].

3.1. Stellar black holes

A new study shows that there are a considerable number of stellar black holes in the universe, as many as 40 million trillion. Everything does not last forever in the universe, and neither do the stars that shine so brightly. A star collapses under its own gravity, and when a star evolves to the end, if there is too much mass left (more than three times the mass of the Sun - the currently estimated maximum mass of a neutron star), it cannot form a dense star of a white dwarf or a neutron star, then there is no other force that can stop the star from continuing collapsing under ultimate gravity, which then abruptly changes to a gravitational collapse, and ultimately forms a dense black hole. It is important to note that there may be a mass gap between the maximum mass of a neutron star and the minimum mass of a black hole.

3.2. Supermassive Black Holes

Astronomers believe that there is a supermassive black hole or holes at the centre of all galaxies [5]. However, scientists do not precisely know how supermassive black holes form. One formation mechanism that is accepted by most is a slow accretion (starting from the size of a star) of dust and gas into the cosmic surroundings, which increases it to a massive size. Another popular theoretical model is that primordial clouds of interstellar gas collapsed together under their own gravity and rapidly gained mass, but this model only applies to primordial gas composed only of hydrogen and helium [6].

3.3. Intermediate-Mass Black Holes

Intermediate-mass black holes were used to be just a theoretical prediction of a type of black hole. Even scientists believed that black holes were only big or small, and there were no black holes between big size and small size. However, this was broken by the signals detected by LIGO’s two interferometers on 21 May 2019, which was the first time that humanity collected precise gravitational wave data of intermediate-mass black holes, and it was an essential milestone in the history of black hole physics [7].

4. Black holes detection

Because black holes are invisible, they have very few direct observation methods. Astronomers mainly use indirect methods to deduce the existence of a black hole. The most common way is to use various accurate telescopes to observe some information made by black holes. Of course, there are also some observation methods through the other stars’ movements, which are influenced by black holes beside them.

4.1. Mutual Motion

In a binary system, according to Newton’s law of gravity, two stars have a centre of mass formed by gravity, and in the balance of this gravity, they move around a shared centre of mass. Astronomers have observed almost 90 stars in the Milky Way since 1995. Through recordings and computer simulations, they have found that the overall trend of the orbits of these 90 stars is a circle. However, the mass of the planets around the two stars also affects the wobble of the binary system. In recent years, astronomers from the Gravity Collaboration have studied a star called S2. They found that it swung around every 16 years, but its orbit did not follow a circular shape. Astronomers used the Very Large Telescope (VLT) in Chile to reconstruct the star’s orbit more accurately. They concluded that the star’s orbit was almost perfectly rosy, as Einstein’s theory of general relativity predicted [8]. Based on the data about this star and its orbit, astronomers found out that it surrounded a target mass 4.3 million times larger than the mass of the Sun, with a radius of about 0.002 light-years. Furthermore, for an object that did not glow and had such a huge mass, it was essentially identified as a giant black hole.

Figure 1 shows that the orbit of a star moving around a black hole is a rose shape just as predicted by the theory of General Relativity.

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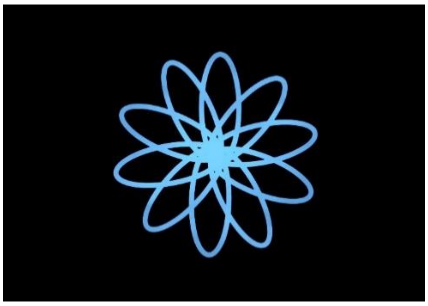

Figure 1. The orbit of a star moving around a black hole is a rose shape

4.2. Scanning Observation Method
The scanning observation method uses satellite telescopes to scan the whole range of the universe. This is because when the black hole swallows the matter, it will produce a robust gravitational effect, which will cause an energy explosion. Scanning telescopes can identify this abnormal increase in energy and locate the black hole. Scanning observation is one of the most common methods of observing black holes, but it also has some limitations. A burst of energy is a prerequisite for this method, but neither are all black holes bursting with energy, nor are they the only ones that can produce vast amounts of energy. For example, a supernova explosion is one of the most spectacular scenes in the universe, and this process releases large amounts of energy and matter.

4.3. Radio Observation Method
The radio observation method uses a giant radio telescope to capture the radio radiation produced by the matter entering the black hole and measure its frequency and intensity to determine the location of the black hole. The radio observation method is also one of the popular methods of detecting black holes, such as the Event Horizon Telescope (EHT), which observed the supermassive black hole in galaxy M87 in 2019 is a radio telescope [9]. Unlike the scanning observation method, radio waves can pass through these cosmic impurities and remain almost unaffected. However, this method needs some demands that the radio signals from the black holes cannot be too weak, and the antenna pointing of the telescope must be constantly adjusted.

4.4. X-ray detection method
Black hole’s accretion disk consists of diffuse material revolving around a central body. Usually, this gas disk surrounds a black hole or neutron star. Friction within the accretion disk makes the gas to spiral down and fall into black holes or stars. A black hole has a great and immense gravitational effect so that when the celestial body isn’t moving fast enough, it will get into the event horizon under the force of gravity. Moreover, when the matter is sucked into a black hole, a spinning accretion disk of gas with high speed will be shaped around the event horizon if there is a conservation of angular momentum. Because of the high-speed spinning of the accretion disk (the closer to the event horizon, the higher the spinning speed), the friction between the gases generates a large amount of thermal energy. Also, as the radiant energy (thermal radiation) gets more stronger, the electromagnetic wavelength of the gas gets shorter. Therefore, we can observe the x-rays released by the high-speed gas in the accretion disk. Generally, X-ray observation is used for the more evident and intense black hole activity phenomena, and it is often used to detect accretion disks and jets. X-ray observation has a disadvantage: the wavelength of X-rays is so short that it is difficult to pass through the Earth’s atmosphere, which makes the observation extremely difficult. However, X-ray observations have been widely used in black hole investigations in recent years, such as NASA’s Chandra X-ray Observatory (CXO), which in August 2022 detected the audio according to the pressure waves of the Perseus Black Hole away 200 million light-years from us.

Figure 2 shows a simple accretion model of a black hole. The yellow area is the black hole’s accretion disc, and the blue area next to it is other objects absorbed by the black hole.

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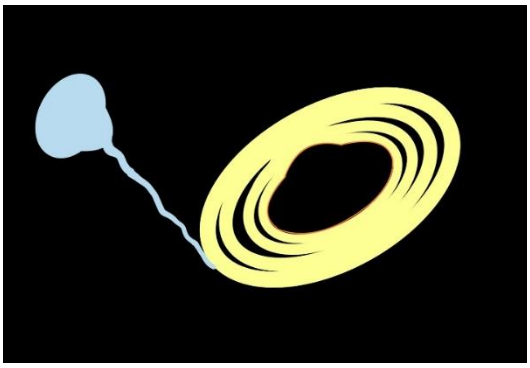

Figure 2. A simple accretion model of a black hole.

5. Speculation and future prospect of black holes

5.1. Hawking Radiation

Before Hawking Radiation Theory came out, there was a puzzle in black hole physics: If an object with entropy [10] was thrown into a black hole, the black hole would swallow it up. So wouldn't its entropy disappear as well? However, entropy only increases in the universe. Did this mean black holes also had entropy? Nevertheless, this contradicted a physical theorem: Any matter that has entropy will release the Blackbody Radiation Law. This indicated that black holes also released radiation outward—one contradictory result after another confused physicists. Since many theories about black holes were rooted only in general relativity, Hawking combined quantum mechanics with general relativity, and then he drew a conclusion that was so difficult to understand that many physicists could not believe it. Hawking said that because the space-time surrounding the black hole was twisted so much, this would cause pairs of virtual particles nearby the event horizon of the black hole to change their proper behaviour (annihilate in a short time) if one of them was sucked into the black hole, while the other virtual particle would transform into a real particle and escaped from the black hole. This also meant that there was matter in the universe that should not exist. If the mass of the black hole did not decrease, it would be against the basic rule of the universe: the law of energy conservation. Thus, some of the energy in the black hole must be transformed into the energy of the escaping real particle to satisfy the rule [11].

For stellar black holes, Hawking radiation theory is almost worthless. Because the mass of stellar black holes is so huge, it is impossible for scientists who spend their entire lives studying them to come up with any results. However, Hawking believes the universe itself may have produced a large number of miniature black holes in the early periods after the time point of the Big Bang [12]. Such miniature black holes would evaporate faster and faster and eventually break up strongly, emitting brief but spectacular gamma rays.

5.2. The Penrose Process

In 1969, The British physicist Penrose proposed that energy could be pumped out of a spinning black hole by dropping an object into it. A spinning black hole has angular momentum (a.k.a. rotational energy), and the event horizon does not enclose this energy. It exists in a unique structure--the black hole energy layer. Besides regular orbits, there are also some negative energy orbits (i.e., orbits of angular momentum), which spin in the opposite direction of the black hole's rotation. Suppose an object falls into the black hole energy layer and splits into two parts at the proper location. In that case, one part falls into the black hole along the negative energy orbit, and the other part escapes from the black hole. The energy of the escaping part will increase [13]. It will be greater than the energy of the whole object in order to obey the law of energy conservation. In an ideal situation, 29 % of the energy of the entire black hole can be extracted from an extreme Kerr black hole. This is much more effective compared to other energy modes, such as nuclear fusion or nuclear fission. Of course, with this process,

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the black hole itself will have less and less energy and angular momentum and may become a Schwarzschild black hole eventually.

6. Conclusion

In summary, this paper presents today's mainstream view (recognized by most astronomers) of black holes. Properties of black holes, detection methods, and the most classical classifications are all mentioned in this paper. This paper further explores the possibility of black holes for future energy supply. The physics of black holes has taken much time to build up, from being treated as a threat by scientists in the past to being studied with great fascination now. However, the future of black hole physics is undoubtedly more than that, and it has the potential but enormous research value. It is like an invisible melting pot in the universe, sucking everything close to it and "creating" new phenomena and laws that have not yet been observed. I believe that there will be more and more important discoveries and results about black holes in the future.

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