Exploring the Mysteries of Black Holes

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Abstract. The study of black holes originated at the forefront of theoretical physics. In the early years, researchers such as Carl Schwarzschild and John Michell proposed early theories related to black holes, which were later supported by observational data. This article first dissects the key scientific concepts of black holes - such as event horizons, singularities, and their impacts on the surrounding spacetime; At the same time, it traces the historical evolution of black hole research and presents in its entirety the entire process from "theoretical conception" to "observational evidence". In recent years, with the development of key technologies such as the Event Horizon Telescope (EHT) and gravitational wave astronomy, human research on black holes has witnessed significant breakthroughs: Nowadays, we can directly "observe" the existence of black holes, and by studying the interaction between black holes and matter and other means, we can gain a deeper understanding of the overall evolution of the universe, the evolution of individual galaxies, and the internal structure of black holes themselves.

Keywords: Event Horizon; Singularity; Gravitational Wave Astronomy; Event Horizon Telescope; General Relativity.

1. Introduction

The year 1971 marked a significant turning point in the understanding of black holes. That year, Princeton University physicist John Wheeler coined the term 'black hole' and formulated the famous no-black-hole theorem. The theorem clearly states that black holes have only three properties: mass, charge, and angular momentum. This simplification decreases the complexity of black hole physics. Although black holes do not emit radiation into space, scientists can verify the existence of black holes by observing their effects on the surrounding region. One phenomenon that indirectly supports the existence of black holes is the high-energy emissions from accreting matter, which arise near the event horizon. More direct observational evidence for the existence of black holes has been found through modern observational tools, such as radio telescopes and X-ray telescopes, which enable scientists to observe the high-speed flow of matter ejected from black holes and the accretion discs of matter surrounding them.

In the previous introduction, we learned that a black hole is an independent star. Still, as a 'loner,' he is often located in the center of the galaxy, and in the continuous release of energy to the outside world, its evolution, and development of galaxies in the universe also play an essential role, but how does this energy affect the galaxy in the universe, and how does it affect the structure of the universe? Structure of the universe? Now, we time-travel back to 2019, when the first human photographs of black holes crystallized our earlier imaginings and studies of these phenomena. Based on this, with the rapid development of gravitational wave astronomy in recent years, we continually update our methods for studying black holes, broaden our understanding, and develop techniques for detecting black hole mergers, black hole-galaxy interactions, and other extreme astronomical phenomena.

At this stage, we are fascinated by the unusual physical properties of black holes, which contradict the fundamental principles of the phenomenon. It always tells us that black holes contain endless possibilities. Through the study of black holes, we have the opportunity to explore high-energy particle physics and quantum gravity theory. With the development of gravitational waves in recent years, our ability to detect spatial and temporal fluctuations has increased, allowing us to understand the movements and changes of black holes more clearly at all times. The 'information paradox,' a characteristic of black holes, makes us wonder why black holes devour information. Fortunately, the interaction between giant black holes, galaxies, and other interesting phenomena provides more clues to promote the subsequent study of matter, energy, and spacetime. As far as our research on black holes is concerned, they serve as a bridge between the microscopic world of particles and the macroscopic world of matter. They are constantly in contact with or exchanging issues with the outside world. Therefore, studying black holes or their derivatives can help us gain a deeper understanding of the universe's structure, origin, and future from various perspectives.

2. Discussion

2.1 Theoretical foundations of black holes

2.1.1 General relativity and gravitational collapse

Human research on black holes is based on the theory of general relativity and the phenomenon of gravitational collapse. Its core idea is that mass and energy bend spacetime, and objects move along the shortest path (called a geodesic) determined by this curved spacetime. The classic Newton's Law of Universal Gravity is also included, which is essential for studying cosmology, black hole physics, and gravitational waves. In general relativity, gravity can be described as a geometrical property (curvature) of spacetime, and this spacetime curvature can be related to the matter in which it is located and the energy and momentum it radiates using Einstein's field equations. The theory predicts several significant impacts, which have been confirmed by studies measuring the unusual advancement of Mercury's orbit, the redshift of light waves, and the effects of gravitational time dilation.

For the time being, we are dealing with the 'gravitational collapse' we were introduced to in general relativity, which tells us that if a sufficiently massive star is compressed by an 'external force' to within the Schwarzschild radius at the end of its life, it will gradually form black holes. When the mass is sufficiently large, the star collapses into a highly dense object, such as a neutron star or a black hole. In the process, it undergoes a massive release of energy, similar to a supernova explosion. The study of gravitational collapse helps us understand the evolution of stars and the universe's extreme physical conditions. It lays a solid foundation for subsequent research on particle physics and cosmology.

2.1.2 Classification of black holes

A black hole is a fascinating and mysterious celestial body. Its density and gravity are so strong that even light cannot escape. It can be divided into three types according to the mass and formation method: stellar-mass black holes, medium-mass black holes, and supermassive black holes. Stellar-mass black holes are about five to twenty times the mass of the Sun and are formed by the collapse of a single star; intermediate-mass black holes, whose formation is still a challenge, can be a hundred to a few hundred thousand times the mass of the Sun; and supermassive black holes, which are often found at the center of galaxies, can be millions or even billions of times the mass of the Sun. Usually, at the end of a massive star's life, a supernova explosion occurs when its internal nuclear fusion stops, causing external matter to eject and the internal core to collapse to form a black hole. In addition, the merger of two supermassive black holes will create a larger black hole in the galaxy's center.

2.1.3 Basic properties of black holes

As we explore the black hole, its mysterious veil is gradually revealed. The most prominent feature is the strong gravity generated by the extreme bending of the surrounding spacetime. It is precise because of this extreme curvature of spacetime that there is an area inside it where the density and gravity are infinite and the laws of physics are no longer applicable, which is called "singularity". Theoretically, a singularity is an infinitely small point, but in the actual high-speed rotating black hole (Kerr black hole), the singularity is an infinitely thin ring.

The 'event horizon' is an interesting feature discovered by human beings while studying black holes. It is precisely because of this feature that we call black holes the 'lonely travelers'; they will block all the information and matter sent to them from the outside world. The reason for this can be traced back to the formation of black holes. We know that the formation of black holes cannot be separated from the strong gravitational force, which is omnipresent, so when the information or matter is close to it, this strong gravitational force will distort the path of the fast-propagating photons, resulting in the image we observe light-years away from the gradual reddish to dark and ultimately disappearing. As a result, all information that reaches the vicinity of the black hole and cannot be returned is invisible to our observers, creating the 'boundary' of the black hole, the event horizon. Obviously, the size of the event horizon is inextricably linked to the mass of the black hole; the larger the mass of the black hole, the larger the radius of the black hole and the larger the corresponding event horizon.

Another property similar to the event horizon is the information paradox of black holes. Stephen Hawking believes black holes can release energy through Hawking radiation and carry almost no information. Makes the information appear to disappear after the black hole evaporates. However, quantum mechanics requires the conservation of information, so this "loss" creates a paradox. Scientists are now proposing a quantum tunnel model, which considers the firewall hypothesis and the "fuzzy ball" structure in background spacetime to explain this paradox.

2.2 Observational history of black holes

2.2.1 Early Indirect Evidence

Due to the existence of the event horizon and the non-luminous characteristics of the black hole, we can't directly observe it. So, what can we do to explore it better? Early indirect evidence for black hole observations consisted mainly of X-ray binaries and gravitational lensing effects. The most representative of these observations of X-ray binaries was the analysis and exploration of Cygnus X-1, from its discovery in 1964 to the 1971 observation that the system produced the brightest X-rays in the universe from the accretion disc around the black hole. Gradually, we can assume that Cygnus X-1 is a typical X-ray binary system, consisting of a dense star and a blue giant. It was not until 2021 that an international team of researchers made more precise measurements of Cygnus X-1, confirming that this black hole is 21 times more massive than the Sun and spinning at 95 percent of the speed of light. It is the only X-ray binary system ever discovered and confirmed to be more than 20 times the mass of the Sun, spinning at an extremely rapid rate.

In the previous account, we can understand that a massive gravitational force exists inside the black hole; the presence of this powerful energy leads to the bending of light as it passes through the black hole. Photons will be affected by it and lead to a change in the path, as in secondary school physics, light through the lens is due to the influence of the internal medium and the phenomenon of refraction, so we will be this kind of light because of gravitational force and lead to the change of the light of the phenomenon known as the gravitational lens effect. In addition, due to the uneven distribution of gravitational intensity, the light is eventually magnified or multiplied, resulting in many unexpected phenomena. From the event horizon properties and the gravitational lensing effect, we know that we cannot directly observe objects light-years away through existing telescopes. However, the outward radiation of black holes never stops, allowing us to learn more about the universe through the intrinsic properties of black holes or their interactions with other celestial bodies.

2.2.2 The Rise of Gravitational Wave Astronomy

In 2015, the first gravitational wave signal, GW150914, was detected for the first time by the Laser Interferometric Gravitational Wave Observatory (LIGO), coming from a merger of two black holes 26 and 39 times the mass of the Sun, confirming the existence of gravitational waves and revealing the existence and behavior of a double black hole system. Similarly, in 2019, we detected the formation of an intermediate mass black hole 142 times the mass of the Sun after the merger, contributing to the origin and formation process of supermassive black holes.

Black holes contain enormous amounts of energy, so the merger of two black holes will inevitably cause a gravitational redistribution that will release a large number of gravitational wave signals, which can be analyzed to deduce the intrinsic properties of the black holes before and after the merger, such as their mass and self-selecting parameters, as well as the amount of energy that was radiated in the process of the merger. The detector designed for gravitational waves allows us to analyze the merger's distance and obtain the universe's expansion rate (Hubble constant) based on its interaction with the outside world. The gravitational wave detector will then be combined with electromagnetic, X-ray, and radiometric waves for a multi-band investigation, providing a more comprehensive understanding of the nature of black holes and the universe associated with them.

2.2.3 Milestone Discovery of Event Horizon Telescope (EHT)

The Event Horizon Telescope (EHT) is irreplaceable in our exploration of cosmology and astronomy. The discovery provides new clues to understanding the material acceleration mechanism and energy output process around the black hole, supplementing the existing model of black hole jets. The landmark discovery of EHF has verified the general theory of relativity and helped scientists to understand and describe physical phenomena in the most extreme environments in the universe more deeply.

2.3 Black hole-matter interactions

The mechanism of black hole generation is based on interactions between the materials that comprise black holes. Accretion discs are the easiest to observe and model among the numerous interactions. This section will discuss the origin, evolution, and interaction of Accraid Discs. In addition, the section on matter's interaction with black hole winds and magnetized plasma will be briefly addressed.

2.3.1 Formation and evolution of accretion discs

Theoretical inferences and conjectures suggest that black holes radiate gravitational waves outward, and it is assumed that black holes and matter are in a constant state of interaction. However, the strongest and most direct evidence of this is found in the accretion discs around black holes. Its formation and evolution involve a variety of physical mechanisms related to celestial bodies and black holes, including energy conversion, gravitational interactions, and others. Accretion discs are formed due to the accumulation of matter during black hole mergers, where the matter is spun up and flattened by the mechanism of conservation of angular momentum. However, they do not remain stable after formation due to thermal and viscous instabilities, among other factors. They undergo unpredictable changes. The accretion rate varies with the gravitational distribution of the black hole, and there are different types of accretion discs, such as standard, optically thick, and elongated discs. In addition, these materials will continuously generate heat and release a large number of electromagnetic rays or X-rays during their movement towards the center of the black hole; due to the strong gravitational force inside the black hole, some of these particles moving towards the center will be accelerated to a speed close to the speed of light and then ejected to form a jet stream.

Currently, we observe accretion discs primarily through direct imaging with high-resolution telescopes and indirectly by studying the high-energy X-rays and radio waves emitted by accretion discs. Inferring the existence of accretion discs and their corresponding properties, as well as further clarifying the chemical composition and energy distribution of the interstellar medium affected by accretion discs, is of great significance to our understanding of the formation and evolution of galaxies, as well as the growth and evolution of black holes.

2.3.2 Black hole winds and magnetised plasma

The black hole wind is a particle flow carrying energy and momentum blown from the black hole or its surrounding accretion disk. Magnetized plasma, on the other hand, is a substance composed of positively charged ions and negatively charged electrons, controlled by magnetic fields. It is electrically neutral but can exhibit complex behaviors under the influence of magnetic fields. Therefore, the evolution of the Milky Way and black holes can be further observed by examining the magnetic field near black holes, the path of light deflection, and the characteristics of jets. Currently, simulation studies are being conducted by combining supercomputers with quantum effect theories, and high-frequency observations are being carried out using a combination of OMEGA laser equipment, the ALMA telescope, and the Comet satellite to unveil further the mysteries of black holes and their surrounding environments.

2.4 Effects of black holes on galaxies and the universe

There are two points of view: one is that the growth of black holes actively drives galaxy evolution, and the other is that galaxies internally govern the development of black holes, i.e., whether the universe gives birth to black holes or black holes give birth to the universe. So far, researchers who support the various points of view have been actively seeking evidence to support their claims, and thus, no consensus has been reached.

2.4.1 Supermassive black holes and galaxy evolution

Supermassive black holes are usually found at the center of large galaxies and have masses of millions to billions of times the mass of the Sun. By studying black holes, we have seen a strong relationship between supermassive black holes and the evolution of galaxies. For example, there is a constant relationship between the mass of a supermassive black hole and the mass of the center of the host galaxy; the mass of a supermassive black hole is related not only to the total mass of the host galaxy but also to the speed of the stars in the outer regions of the galaxy, due to the effect of the black hole on the internal dynamics of the galaxy.

Furthermore, the evolution of galaxies and their central supermassive black holes appears to be synchronous on long timescales and to interact and influence each other. On the formation side, the energy released by the black hole during accretion affects the distribution of stellar gas. In contrast, the rate of stellar activity affects the growth of the black hole by increasing the flow of material into the black hole. On the gas side, the mass of a black hole modulates a galaxy's atomic hydrogen gas content in an inverse relationship, which affects the galaxy's evolution.

2.4.2 Shaping of the structure of the universe by black hole mergers

In addition to the influence of supermassive black holes on the universe, the merger of black holes constantly affects the universe, from the generation of gravitational waves to the impact on the surrounding environment and even the shaping of the universe's structure.

Regarding gravitational waves, the strong gravitational waves generated by the merger of two black holes propagate at the speed of light. They are accompanied by a significant energy transfer, which enables the precise measurement of the merger's parameters, including the masses, spins, and distances of the black holes. It provides a new observational window for astrophysical research, allowing us to understand the universe's history and the nature of dark matter. For host galaxies, black holes generate large tidal forces during mergers, which trigger or enhance the activity of active galactic nuclei, and thereby affect the evolution of the host galaxies. For the surrounding environment, a large amount of energy is released during the merger process, which heats the atmosphere and leads to gas cooling, condensation, and other effects. In addition, the merged black holes generate powerful outward jets and outflows, which affect the formation and evolution of stars in the nearby areas. On the cosmic scale, as the saying goes, 'little makes much'; a single black hole may have a negligible impact on the universe, but when tens or hundreds of millions of merger events occur together, they will affect the evolution of the universe and the formation of large-scale structures to a certain extent.

2.4.3 The connection between black holes and cosmology

As we can see, black holes and the universe are closely interconnected, from the large-scale structure of the universe to the smallest particles of dust. Therefore, we can gradually understand and explore the mysteries of dark matter and dark energy, as well as the early conditions of the universe, related to black holes. We can precisely measure the expansion rate and age of the universe through the cosmological parameters that describe the properties of black holes, and further understand the formation of the universe's large-scale structure by studying the mass, formation, and distribution of black holes.

3. Conclusion

In the past, we knew nothing about black holes, but in recent times, with the continuous development of physics, we have gradually lifted their mysterious veil. From the time Einstein predicted the existence of black holes through his theories to the present, when we can obtain high-resolution images of black holes through advanced technological means, we have traveled hundreds of years and will continue to go further. Therefore, in this paper, we discuss the interactions and connections between black holes and matter, as well as the universe, from the theoretical foundations and observational history of black holes. We explore the existence and fundamental nature of black holes from the perspective of general relativity. Due to its powerful gravity, light or other information traveling at the speed of light cannot escape and, therefore, cannot be directly observed. However, scientists have gradually unravelled the mystery of black holes indirectly, such as by observing high-energy radiation and gravitational lensing effects. With the advancement of science and technology, particularly the application of radio telescopes, X-ray telescopes, and ultra-high-frequency telescopes, scientists are now able to measure high-precision properties, such as the mass and rotational speed of black holes, with greater accuracy. That has even provided direct evidence for the existence of black holes. To date, human research has made gradual progress, but we have not yet fully unveiled the secrets of black holes. Research on black holes continues to explore the information paradox, singularity, internal structure, and other cutting-edge issues. However, in the current study, several difficulties arise regarding the theories and observations of black holes, including the explanation of singularities and the lack of a unified theory related to quantum gravity, as well as significant gaps in the observation of black holes. Therefore, we must continue to strive for new theoretical breakthroughs and technological innovations to gain a deeper understanding of the field. Advancements in observational techniques, such as the next-generation EHT and planned space-based gravitational wave observatories like LISA, will bring us closer to unraveling these mysteries. Black holes will continue to drive innovation and deepen our understanding of the cosmos.

4. Evaluation

Before the project began, my knowledge of black holes was limited to my childhood science education, and this was the first time I had learned about black holes in a systematic and in-depth manner. Throughout this period, I have been introduced to the universe as a novice, and this is no longer just a project, but a means to expand my knowledge and understanding. It has given me a new sense of the fundamental properties of black holes, their observational history, and the interaction between black holes and other matter. Nowadays, whenever I look up at the sky, I can't help but ask, 'Is there a star explosion and evolution going on in the vast universe tens of thousands of light-years away?' and 'Is a black hole on the other side of the Milky Way constantly flooding the universe with information?' These questions make me ponder. Questions kept me thinking deeply. In addition, after the project, the mysteries of the universe continue to fascinate me, so I will continue to pay attention to the study of black holes and their latest progress and continue to learn about them to gain a deeper understanding of the various types of related research. At this stage, the research on black holes has developed rapidly since the first photograph of a black hole was released. However, there are still various difficulties due to its event horizon and information paradox, which makes me realize that I need to take every step steadily in my research to achieve a significant leap forward by accumulating more knowledge. As for the thesis, the experience I gained this time has made me clearer about organizing my logic to express my views better. Looking back on the entire project, I believe the most significant deficiency is that I lack a solid understanding of the basic theory of black holes, and I need to learn more about it. Therefore, during the project, I identified the challenging points in the data and addressed the questions after completing the daily study plan by combining online resources and paper books to gain a deeper understanding of the topic. Ultimately, I aim to enhance my proficiency in utilizing software for data access and related applications.

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