Exploring The Formation and Dynamics of Black Holes

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Abstract. Black holes, created by the collapse of massive stars, are one of the most mysterious phenomena in astrophysics. Understanding their formation and behavior is crucial to understanding the evolution and structure of the universe. However, significant gaps remain in the understanding of their origins and characteristics. This study delves into the complexities of black hole formation, dynamics, and classification, aiming to unravel the mysteries surrounding these cosmic entities. This article uses a combination of the theoretical framework of general relativity and numerical simulation. The study investigated various scenarios for black hole formation, including stellar collapse and mergers. Observational data from telescopes such as Hubble and Webb complement the theoretical analysis. This article provides a comprehensive overview of stellar evolution and the stages leading to the formation of black holes. It discusses the theoretical foundations of black hole physics, including key indicators such as Schwarzschild, Kerr, and Kerr-Newman. In addition, through theoretical analysis and simulation, research has revealed the formation mechanisms of different types of black holes, including stellar-mass black holes, intermediate-mass black holes, and massive black holes. The findings deepen understanding of black hole dynamics while highlighting the limitations of existing theoretical models.

Keywords: Black holes; Formation and evolution; Classification.

1. Introduction

The black holes have perplexed many astrophysics because of their invisibility. Most investigation in it is based on theoretical work and calculation. By contrast, the formation and death of stars are relatively clear. Over the past several decades, astrophysicists have changed their opinions on black holes strikingly. The black holes have been more and more important in studying the total cosmic evolution and structures because the black holes are the product of the death of stars.

The finding of black holes came from Einstein's general relativity. By solving one of its vacuum solutions, black holes were first proved to exist. After seven decades, more and more theories came up. Some thought the massive black holes could be created directly from the cosmic dust or the death of stars. Some thought that black holes could be created only when two black holes collide, which is challenged with further observation. The existence of intermediate black holes and charged black holes is still not clear because of little evidence. The formation of them, and how they will evolve and form is still an attractive mystery. Black holes, fascinating entities originating from the collapse of massive stars or primordial density fluctuations, challenge observational and theoretical exploration due to their elusive nature. Rooted in General Relativity, they are described by exact solutions such as the Schwarzschild, Kerr, and Kerr-Newman metrics, offering insights into their characteristics influenced by mass, rotation, and charge. The dynamic interactions of black holes, particularly during mergers, require numerical simulations to comprehend fully. However, theoretical complexities, including the distribution of mass and energy within black holes, pose challenges and yield paradoxical outcomes, as evidenced by studies like those of Penrose and others. These investigations not only deepen the understanding of black hole dynamics but also underscore the limits of the current theoretical frameworks, prompting continued exploration at the forefront of gravitational physics.

The paper by describing the process of star evolution and death, as well as the formation mode and classification of black holes, this paper deeply explores the origin and nature of black holes. Combined with extensive theoretical and numerical simulations, it provides an important basis for understanding the evolution and structure of the universe. The paper aims to fully understand how black holes form and how different types of black holes affect the universe.

2. Stellar Evolution and Stellar Death

Stellar evolution and death, play a significant role in the formation of a black hole.

A star is a massive celestial body that contains large internal energy and shines. Stars can be classified in lots of ways, like in the phase they are in, their size, and their spectrum. Here, the paper focuses on the phase the stars are in. In this way, stars can be classified into new stars, main sequence stars, red giants, and supernovae. The supernovae include white dwarfs (a low-brightness celestial body), neutron stars (a high-density celestial body), and black holes. It would discuss black holes in more detail.

First, stars originate from huge molecular clouds of mainly hydrogen and helium. Most void in a galaxy has a density of about 0.1 to 1 atom per cubic centimeter, but giant molecular clouds have a density of millions of atoms per cubic centimeter. A giant molecular cloud contains hundreds of thousands to tens of millions of solar masses and is 50 to 300 light-years across. When supernova explosions and huge collisions happen, gravitational perturbations are created and then the cloud collapses. After that, more and more cosmic gas and dust gather at the center of the cloud, forming swirling nebulae. Then the temperature and pressure of the cloud become greater and greater, forming a disk nebula. The disk nebula is constantly being squeezed, forming super-hot and dense spheres and then emitting gas columns. Then the angular velocity and momentum of the cloud keep getting greater. More and more dust and gas are drawn into the cloud. Accretion disks and tidal bodies are formed. The cloud emits bipolar jets.

In more than 500 thousand years, the atomic temperature has reached over 1.5 million Celsius degrees. After a nuclear fusion, a star is created. At this time, this star is at least one-tenth the mass of the Sun. After the star uses up all the hydrogen in its core and the hydrogen in the core is consumed, the nuclear reactions in the core stop, leaving a helium core. Losing the energy of the nuclear reaction to resist gravity, the star's outer shell begins to gravitationally collapse. The inner temperature and pressure would increase, which happens as well during the formation phase. This is because hydrogen-rich materials outside the zone of hydrogen exhaustion are pulled inward to higher densities and temperatures during the core's contraction and cooling when it ignites [1]. The core begins to undergo helium fusion, re-generating energy through nuclear fusion to resist gravity. If the mass of the star is not great enough to fuse helium, the star would release heat and then become a red dwarf.

Small mass stars, cannot use up their internal hydrogen as the age of the universe is considered as approximately 10 billion years. Some small stars don’t explode to become planetary nebula. They just become red dwarfs. Some other small-mass stars (smaller than half of this star), even don’t go through a helium reaction. They are just becoming dimmer and dimmer when they are going to die. For intermediate-mass stars, they tend to become planetary nebula. Because the rate of expansion is greater than the rate of change in energy, temperature decreases, and then these stars become red giant stars. For big mass stars, their brightness is not much greater than that of small ones because their helium has been ignited before electron degeneracy pressure becomes very great. These stars are called red supergiant stars after its shell dilates. Supergiants that vary photometrically and spectroscopically, fairly irregularly, on timescales of years. They also undergo occasional giant eruptions, in which tens of solar masses are ejected [2]. After that, the supernova explosion happens and the substance the supergiant emits can crash into comets and form new stars, planets, or other celestial bodies.

After the supernova explosion, the death of stars is coming. Stars can become white dwarfs, neutron stars, and black holes depending on their different masses. Smaller-mass stars tend to become white dwarfs but not black holes or neutron stars. When electrons are compressed into the nuclei, and protons and electrons combine to become neutrons, neutron stars are created. Most angular momentum is reserved in the neutron stars, which makes their speed of rotation very fast. These stars' internal cores have a mass between 1.44 times the mass of the sun and 3.2 times the mass of the sun.

3. The Form of Black Holes

After the neutron stars keep absorbing substance, the neutrons can be crushed and neutron stars can have great enough mass to form black holes. Also, generally, for greater-mass stars, because of the large mass they contain, neutron degeneracy pressure is not enough to prevent collapsing, and then the stars can easily collapse to be under Schwarzschild radius, which creates black holes.

Here it discusses the classification of black holes first. There are several ways to classify black holes, according to the properties they have, including in mass, in whether they spin and have charge. For mass, there are stellar-mass black holes (SBH, having mass close to stars), intermediate-mass black holes (IMBH, having mass between stars and galaxies), and massive black holes (MBH with a mass several million times that of the sun). Generally, SBH forms when large-mass stars experience supernova explosions and then become black holes after their sizes are under the Schwarzschild radius. There is less evidence of the existence of IMBHs. There are several theories to explain the formation of intermediate-mass black holes. The first one states that two stellar-mass black holes combine to become a new IMBH. The second one states that two stars can combine to become an intermediate black hole. The third one states that the accretion disks in an active galactic nucleus combine to form intermediate-mass black holes. For MBHs, the main theory for its formation was the collisions of two SBHs. With more and more observation, this theory was challenged because there are MBH several million light years away from Earth. Because at that time when they formed, there were little stars in the universe. The first stars appeared in low-mass dark matter haloes about a few 100 million years after the Big Bang [3]. So the collisions of two SBHs were not possible. There is also an embryonic theory of supermassive black holes to explain the formation of MBH. It states that the seeds of MBHs increase their volume during inflation. Some of them are close to the center of the Big Bang, they can form MBHs during inflation. The material forming the MBHs must be the same material from which galaxies and the rest of the universe are composed [4]. It is also convincing that MBHs with substantial initial masses, thousands to millions of M⊙, can form as a consequence of dynamical instabilities that involve either the gaseous or stellar content of proto-galaxies [4]. There are also simulations to show that streaming motions—velocity offsets between the gas and dark matter components—could have produced black holes with tens of thousands of solar masses in the early universe [5]. Also, when discussing their charge and spin, it can classify black holes into the Schwarzschild black hole(no charge, no spin), the Kerr black hole(with spin but not charge), the Reissner-Nordström black hole （with charge but no spin) and the Kerr-Newman black hole(with both charge and spin). Among these black holes, the Kerr black hole is considered to be the most possible one. The Kerr metric can be expressed as:

$$\mathrm{ds}^2 = 1 - \frac{\mathrm{rr_g}}{\tilde{n}^2}\mathrm{c}^2\mathrm{dt}^2 + 2\frac{\mathrm{rr_g}}{\tilde{n}^2}\mathrm{asin}^2\grave{e}\mathrm{d}\ddot{o}\mathrm{cdt} - \frac{\tilde{n}^2}{\mathrm{r}^2 + \mathrm{a}^2 - \mathrm{rr_g}}\mathrm{dr}^2 - \tilde{n}^2\mathrm{d}\grave{e} - (\mathrm{r}^2 + \mathrm{a}^2 + \frac{\mathrm{rr_g}}{\tilde{n}^2}\mathrm{a}^2\mathrm{sin}^2\grave{e})\mathrm{sin}^2\grave{e}\mathrm{d}\ddot{o}^2$$

$$\rho^2 = r^2 + a^2 cos^2\theta$$

$$r_g = \frac{2GM}{c^2} \quad (1)$$

Black holes are amazing objects that are so difficult to observe that they can only be studied in a mainly theoretical manner. The idea of a black hole has its roots in Newtonian mechanics. When researchers calculate the cosmic escape velocity, they find that the radius squared is inversely proportional to the velocity. Because the particle theory of light predicts that light has a certain velocity (locality of light), the escape velocity of some massive, low-density stars may be greater than or equal to the speed of light. This means that the star does not emit light from its surface into space at all, and to an observer far enough away, the star is completely black. This is a mistake in classical theory, but the radius of the black hole coincidentally coincides with the answer given by general relativity (Schwarzschild's solution). In this section, the paper will focus on the origin of black holes and how large black holes form.

The leading explanations for black hole formation are:

1. During the Big Bang, the uneven inflation of space caused local mass to collapse into black holes. Such black holes are usually located at the center of the local galaxy or local supergroup of galaxies.
2. As the universe evolved, stars lost energy as they aged and their mass collapsed into black holes. Such black holes are usually small in mass but may become large later due to the surrounding matter or nebula.

In general, relativity, can give exact solutions for three simple black holes: the solution for a stationary, non-rotating Schwarzschild black hole, the solution for a stationary, rotating Kerr black hole, and the solution for a stationary, charged Kerr-Newman black hole. It can use these combinations to describe a realistic black hole.

The metric it be used here to describe the dot product of a vector is $g_{\nu}{}^{\mu} = diag(-1,1,1,1)$.

For the simplest Schwarzschild black hole, its surroundings can be described using the following metric

$$ds^2 = \left(1 - \frac{2m}{r}\right) dt^2 - \left(1 - \frac{2m}{r}\right)^{-1} dr^2 - r^2 d\Omega^2 \tag{2}$$

This is a description of the distance in a spherical coordinate system, where r is the distance from the center of the black hole (here r's so-called distance is still the distance from the singularity in Euclidean geometry).

Similarly, with the rotating Kerr black hole, it can add some special terms of rotation to the Schwarzschild black hole, whose metric description is

$$ds^2 = \left(1 - \frac{2m\rho}{\rho^2 + a^2\cos^2\theta}\right) dt^2 - (\rho^2 + a^2\cos^2\theta) d\theta^2 - \frac{\rho^2 + a^2\cos^2\theta}{\rho^2 + a^2 - 2m\rho} d\rho^2 - \left[(\rho^2 + a^2)\sin^2\theta + \frac{2m\rho a^2 \sin^4\theta}{\rho^2 + a^2\cos^2\theta}\right] d\varphi^2 - \frac{4m\rho a \sin^2\theta}{\rho^2 + a^2\cos^2\theta} dt d\varphi \tag{3}$$

Of course, for a charged black hole with a net charge in space, it can use the Kerr-Newman black hole metric to describe the distance around it, and its metric is described below:

$$ds^2 = -\left(1 - \frac{2Mr - Q^2}{\rho^2}\right) dt^2 + \frac{\rho^2}{\Delta} dr^2 + \rho^2 d\theta^2 + \left[(r^2 + a^2)\sin^2\theta + \frac{(2Mr - Q^2)a^2\sin^4\theta}{\rho^2}\right] d\varphi^2 - \frac{2(2Mr - Q^2)a\sin^2\theta}{\rho^2} dt d\varphi$$

$$\rho^2 = r^2 + a^2\cos^2\theta$$

$$\Delta = r^2 - 2Mr + a^2 + Q^2 \tag{4}$$

The solution of these static black hole metrics is not very simple, for the black hole in motion, even the dynamics of the interaction of two black holes can only rely on the numerical simulation of the computer. However, the numerical solution of the black hole surrounding the environment is often strange. This is also a difficult problem in the hypothesis of the formation of intermediate-mass black holes, and how to simulate the black hole merger.

The formation of black holes is related to the distribution of mass and energy. For isolated systems, the curl of the dynamic tensor is conserved. Since the density of a black hole is related to its size as follows

$$r = \frac{2GM}{c^2}$$

$$\rho = \frac{M}{\frac{4}{3}r^3}$$

$$\rho = \frac{3*c^3}{4\pi*8G^3M^2} \quad (5)$$

When the size of the black hole is large enough, it is thought that the matter inside the black hole can be distributed over more than just the singularity. At the same time, as the black hole absorbs other matter, there must be a process in which matter lies within the black hole's event horizon, but not above the singularity. However, in the study of Penrose et al., they found that if there is mass in the location outside the singularity inside the event horizon of the Schwarzschild black hole, it will lead to negative energy and time solutions inside the black hole [6]. This does not make sense in general relativity.

4. Conclusion

The black holes can be created when stars collapse under the Schwarzschild radius. The black holes can be understood more clearly with further observation done by Hubble and Webb telescopes indirectly. With the current study, already know the possible ways to form massive black holes and possible kinds of black holes, including the Schwarzschild black hole, the Kerr black hole, the Reissner-Nordström black hole, and the Kerr-Newman black hole. But people don’t know whether massive black holes can be formed only in one way or in several ways that have supposed the formation of several black holes that contain charge and spin or not. People also need to ask how black holes can affect the external galaxies after they evaporate. Meanwhile, the total review of theories on the formation of black holes is meaningful. Further investigation into the specific process of forming different black holes has broad prospects and can help understand the evolution and structure of the universe.

Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

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