

The Relationship between Supernova Explosions and Black Hole Formation

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Abstract. The interaction between supernova explosions and black hole formation is a significant study in astrophysics, explaining the map of cosmic evolution. This study delves into the late stages of a star's life cycle, the evolution of white dwarfs and neutron stars, and the early stages of black hole formation. Through the fusion of theory and data observation, the study has deepened the understanding of stellar evolution cycles and revealed the complex process of black hole origin, as well as the internal and external conditions required for its formation (such as binary star systems with certain conditions). In addition, the study revealed that the principles of quantum mechanics are the foundation of celestial evolution, elucidating how the Pauli exclusion principle explains the transition from white dwarfs to neutron stars and ultimately to black holes based on stellar mass. By analyzing these phenomena, the profound connection between celestial evolution and the principles of quantum mechanics is emphasized, and this study helps to broaden the horizons of astrophysical exploration.

Keywords: Supernova, black-hole, stellar collapse, black-hole formation, supernova explosion.

1. Introduction

Supernova explosions and the creation of black holes are important fields in astrophysics, which are part of the evolution process of the universe. They involve the life cycle of stars and black hole physics. At the same time, in-depth research on this topic can help explain some phenomena observed in the universe, provide references for future observation tasks and experiments, and promote the development and innovation of astrophysics.

Two astronomers, Baade and Zwicky, began modern research on supernovae in the 1930s [1]. They found that supernovae are rarer and brighter than common novae, and conclude in the literature is that supernovae are produced by dying stars collapsing into neutron stars through extreme explosions [2]. When the nuclear fuel of a star is depleted and the radiation pressure of the core is no longer able to counteract its gravitational pull, the star will undergo collapse, and its life will end [1]. The large amount of energy deposited during the collapse of a star causes it to explode, and the resulting material eventually falls back into a neutron star or black hole [1].

Supernovae can be classified into various types, corresponding to different forms of stellar death [3]. The first type is Type Ia, which is formed by a thermonuclear explosion from accreting a white dwarf [3]. Other types, such as Type II, Ib, and Ic, are formed when the iron core of a massive star collapses into a neutron star or black hole [3]. This implies that stars of lesser physical mass will eventually evolve into white dwarfs following the explosion. In contrast, stars of greater mass will ultimately transform into neutron stars or black holes. The collapse of a supernova core may form a black hole, which is elucidated as an area where the spacetime gravitational field is infinitely strong to the point where even light cannot escape [4]. Hence, this implies that any particles or signals within the black hole cannot escape the event horizon since the speed of light has attained the maximum velocity for physical transmission [4]. These characteristics indicate that further exploration and research of black holes are currently limited by technology and require the development of new methods, which adds a sense of mystery to black holes and has become an important field for the scientific community to explore the universe.

This study explores the close relationship between supernova explosions and black hole formation. This research focuses on the conditions required for black hole formation after supernova explosions and the different types of black holes that can form. Through theoretical analysis, numerical simulations, and observational data, this research seeks to improve comprehension regarding the pivotal phases of stellar development, investigate the processes involved in creating black holes, and present fresh viewpoints and perspectives.

2. Three Types of Celestial Bodies After the Death of a Star

Dead stars may form three physically different celestial bodies: white dwarfs, neutron stars, and black holes, which need to be explained using the Pauli exclusion principle in quantum mechanics. This principle refers to the fact that no two identical fermion charges in an atom or molecule can have the same quantum state [5]. After the end of a star's lifespan, stars with smaller masses (approximately less than or equal to 8 solar masses) will collapse into white dwarfs, which resist their gravity through the repulsive force of electrons. Stars with higher mass (approximately greater than 8 solar masses) cannot resist their gravity in this way, so they will undergo further collapse to form neutron stars, which means that all their protons and electrons are fused to form neutrons. In this way, the nuclear repulsion generated between neutrons can resist their gravity. If the mass of a dead star is still too large (approximately greater than or equal to 20 solar masses) for the Pauli exclusion principle to counteract its gravity, it will implode into a black hole [6]. In summary, the celestial body formed after the death of a star is related to its mass.

A black hole is like an ideal blackbody, and due to its strong gravity, it is a celestial body with an escape velocity surpassing the speed of light, making it impossible for light, other electromagnetic waves, and any object to escape from it [7]. Currently, black holes are considered to have a wide range in mass, and astronomers typically classify them based on their mass sizes. Among them, black holes can be categorized into three groups according to their mass: stellar mass, intermediate mass, and supermassive mass [8]. Researchers theorize that black holes of stellar mass originate from supernovae caused by the collapse and subsequent rebound of massive stars. When the mass of the material left behind by the explosion is about 20 times or more than the mass of the Sun, celestial bodies will implode into stellar-mass black holes [8]. Supermassive black holes are commonly found at the core of nearly every sizable galaxy, boasting masses that vary from tens of thousands to billions of times that of the Sun. It is still uncertain how these massive celestial bodies were born [9]. However, it can be conjectured that they might have arisen from the collapse of certain supergiant stars during the infancy of the cosmos. During their subsequent expansion, they could have engulfed additional cosmic entities like smaller black holes and neutron stars, or fused with other supermassive black holes, thereby augmenting their mass [9]. Intermediate mass black holes are of course larger than stellar mass black holes and smaller than supermassive black holes, with masses spanning from tens to tens of thousands of times that of the Sun. Currently, this link is missing because no black hole has been scientifically confirmed to have intermediate mass [9].

3. Mechanisms and Types of Supernova Explosions

3.1. The Physical Process of a Supernova Explosion

A supernova is a powerful explosion caused by the explosive thermonuclear combustion of a white dwarf or the gravitational collapse of a star. After the explosion, the material was ejected at up to 15000 to 40000 kilometers per second [10]. Supernovae commonly happen during nuclear transformations within white dwarfs or the concluding phases of the life cycle of a select few massive stars (with masses surpassing 8 solar masses). White dwarfs are initially formed by low-mass stars that have burned out their nuclear fuel and died, and their centers can be ignited again by a sudden atomic mutation, resulting in supernova explosions. A white dwarf primarily consists of carbon and oxygen. When in a binary system, its gravitational pull will siphon material from its companion star, accumulating mass on the white dwarf and initiating a collapse [11]. Due to the rapid compression

and heating of carbon and oxygen, the core of a white dwarf star burns and disintegrates explosively [11]. And for the form of the explosion caused by the collapse of stars, the dying star no longer has enough fuel to generate outward pressure, causing its outer shell to collapse towards the center continuously. The temperature and density inside the star also continue to rise, and the material reaches an almost incompressible density. Finally, the core rebounds, generating a strong shock wave that breaks through the collapsing outer shell and triggers a supernova explosion [11].

3.2. The Types of Supernova Explosions

Supernovae can be classified into two types based on their different explosion modes, Type I and Type II. The distinction between the two types of supernovae is that the brightness and expansion rate of the first type of supernova are four times and twice that of the second type, respectively. In addition, its spectrum does not include hydrogen lines that can be found in type II supernovae [12]. Type I supernovae can be further categorized into three groups based on their spectra: Ia, Ib, and Ic. The mechanisms behind their explosions remain ambiguous [12]. However, there are sufficient reasons to suggest that Type Ia supernovae are the result of white dwarf explosions in binary systems with masses close to Chandrasekhar ($1.4 M_{\odot}$), but it is still uncertain [13]. Type II supernovae are massive stars that, as they conclude their active stage, have exhausted the fusion fuel that generates outward thrust from their cores, rendering them unable to balance their gravitational resistance to the outer shell [12]. This causes the stellar shell to collapse inward until the core reaches its maximum density (10^{13} times that of tungsten) and stops collapsing [11]. The material that falls towards the core due to immense gravity rebounds upon contact with the hard core, ejecting material outward and generating shock waves that spread into the universe [12]. Ib, Ic, and other supernovae in Type I are also believed to be caused by the gravitational collapse of the same stellar nucleus. Supernova explosions are so powerful that they can reorganize the structure of elements to produce new and primordial elements, making them an important origin of elements in the universe. The shock waves generated also help astronomers measure the distance and the rate of expansion of the cosmos [11].

4. The Connection Between Supernovae and Black Hole Formation

There is a close connection between supernova explosions and the formation of black holes. The process of these two phenomena demonstrates that supernova explosions are an inevitable result of the late-stage evolution of stars, while also revealing that black holes are products of extreme gravitational fields that can be understood using simple mathematical techniques, thus having a significant impact on the establishment of astrophysics.

Supernova explosions have a crucial impact on the development of the cosmos. The copious energy and matter released during the detonation of these colossal stars enhance the chemical components in the universe and profoundly influence galaxies. For example, the elements released by explosions can enrich the interstellar medium, allowing the subsequent generation of stars and planets to have more elements during their formation. These elements provide the material basis for the formation of stars and planets and can promote the emergence and evolution of life. Therefore, supernova explosions can not only shape galaxies and their chemical composition, but also promote the diversity of life in the universe. Overall, the study of supernova explosions contributes to an enhanced comprehension of the progression of the cosmos and the inception of life for humankind.

The study's conclusion shows that supernovae are explosions of enormous energy produced by massive stars after their life span, and black holes may be the remnants left behind by these explosions. The connection between supernova explosions and the formation of black holes reveals fundamental physical processes in the universe's evolution, including the life cycle of stars, material collapse, and the manifestation of gravitational fields. At the same time, the energy and matter released by explosions enrich the universe's elements, and promote the formation and evolution of galaxies, and black holes play an essential role in the universe, affecting the structure of surrounding space. Future research can focus on the details of supernova explosions and black hole formation processes, such

as the evolution of black holes. Deeper observations and simulations can help better understand these celestial phenomena and validate existing theoretical models. Overall, supernova explosions and black hole formation represent important components of extreme physical phenomena in the universe.

5. Conclusion

This article explores the connection between supernovae and black holes and reveals the important part they play in the universe. Supernova explosions and black hole formation belong to the study of the extreme physics of the cosmos, which enhances human understanding of the inception and progression of the universe. Scientists will discover a deeper connection between supernovae and black holes and unravel more mysteries of the universe through wider exploration and deeper research.

The development of science and technology has enabled astronomers to use advanced observation equipment to produce accurate data and high-performance computer simulation studies, which has further enabled mankind to have a more in-depth understanding of the two celestial phenomena. With future technological developments and innovations in research methods, when some new supernova phenomena and the existence of more black holes are observed, scientists expect to unravel the more complex connections between supernovae and black holes, explore more puzzles about the evolution and composition of the Universe, and refine human knowledge of the Universe.

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