# *The Discovery History of Black Holes*

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***Abstract:*** With the growing interest of the public in the mysteries of the universe and the continuous achievements in the field of aerospace, it has become essential to introduce the enigmatic celestial bodies of the cosmos—the black holes. This paper will outline the historical journey of human understanding of black holes, their classification, the possible mechanisms of their formation, and some cutting-edge findings aimed at stimulating the readers' interest. This review article is designed to provide readers with a basic understanding of black holes from a historical and categorical perspective. This thesis finds that, although the development of the concept of black holes involves numerous complex theories and a protracted process of exploration, the historical trajectory of their discovery and the detailed classification thereof conform to the logical progression of human cognition. Moreover, this process enables the integration of black holes into the existing astrophysical framework, thereby rendering it more complete.

***Keywords:*** Black Hole, Evolution, Mechanism, Classification

## 1. Introduction

Black holes, celestial bodies with an extremely high mass-to-volume ratio, have evolved from theoretical conception in the 18th century to practical detection in the 21st century. During this period, scientists have classified black holes and provided theoretical explanations for the formation of micro black holes, stellar-mass black holes, intermediate-mass black holes, and supermassive black holes. They have also used theories such as relativity to locate black holes in the universe and verify existing theories.

This paper employs a review research method. The purpose of this paper is to organize the significant events from the inception of the black hole concept to the perfection of its theory and the success of practical detection, and to present the classification, potential formation mechanisms, and related cutting-edge research findings of black holes, in the hope that readers can have a clear concept of black holes, thereby broadening their horizons and enriching their knowledge.

## 2. The Theoretical Discovery of Black Holes

If a celestial body has a sufficiently large mass and a sufficiently small volume, its gravitational force becomes so strong that not even light can escape, thus forming a black hole [1]. This explanation, while not rigorous, vividly depicts the characteristics of black holes.

This paper will begin with the human journey of understanding black holes, step by step, explaining how they were discovered.

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People are accustomed to thinking about more distant matters by starting with examples from their surroundings, and black holes are no exception. In 1783, the British clergyman and natural philosopher John Michell, in a letter to Henry Cavendish, proposed the concept of a "dark star," and the renowned French scholar Pierre-Simon Laplace independently proposed the idea of a "dark star" in 1796 [2]. Their work was based on Newton's classical theory of gravitation and the particle theory of light: if the kinetic energy of photons on the surface of a star is less than its gravitational potential energy, the photons will not be able to escape to infinity [2].

However, Newton's framework of mechanics did not limit the speed of physical signals; the speed of light could easily exceed $3\times10^8$m/s through changes in the reference frame, and action at a distance also allowed forces to be independent of the type of particles involved. In other words, Newton's theoretical system did not have a limit on the escape of information, nor did it have a true black hole that brought confusion and difficulties.

The situation changed with the proposal of Einstein's general theory of relativity, in which time and space are not a priori separated but are integrated into a four-dimensional object. This means that the connection used to describe the curvature of spacetime is uniquely determined by the "metric of spacetime intervals", that is, the metric [2]. By solving the first solution of the accompanying Einstein field equations of gravity, the Schwarzschild black hole was theoretically born. Subsequent debates focused on what the region is outside the singularity with a radius equal to its zero solution and how to test the existence of such a "black hole" if it does exist.

## 3. The Actual Detection of Black Holes

As a special solution to Einstein's field equations of gravity, black holes are a product of pure theoretical research. The existence of black holes in the universe has long been doubted, and Einstein himself did not believe in their existence [3]. However, there are currently two feasible methods to detect black holes: direct measurement and indirect detection.

Direct measurement can be done through gravitational waves produced by black hole collisions. Gravitational waves are ripples in spacetime, that is, fluctuations in spacetime itself propagate outward from the radiation source in the form of waves [3]. By detecting the metric perturbations that travel at the speed of light, gravitational wave signals can be identified. In fact, on September 14, 2015, the Laser Interferometer Gravitational-wave Observatory (LIGO) in the United States first directly detected the gravitational wave signal (GW150914) from the merger of two black holes. This observation not only directly confirmed the existence of gravitational waves but also the existence of black holes.

Indirect detection mainly involves monitoring the accretion disk or companion star around a black hole to determine its existence [3]. When a black hole consumes surrounding matter, it forms an accretion disk and emits different electromagnetic waves, which can be used to detect its presence.

A significant event in 2019 was the release of the first image of a black hole (Figure 1), which was also detected using electromagnetic waves around the black hole. For quiet black holes without accretion disks or companion stars, the strong gravitational pull of the black hole can disrupt the motion of nearby stars. The motion of a bright companion star can be used to infer the presence of a black hole and measure its mass [3].

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Figure 1: The first image of a black hole obtained by the Event Horizon Telescope. The black hole is located in the galaxy M87 of the Virgo Cluster, 55 million light-years from Earth, with a mass 650 million times that of the Sun (imaged from the Event Horizon Telescope collaboration).

## 4. Classification and Possible Formation Mechanisms of Black Holes

### 4.1. Classification of Black Holes

#### 4.1.1. Micro Black Holes

Micro black holes, also known as mini black holes or primordial black holes, have masses close to or much less than that of the Sun. It is currently believed that these black holes originate from the collapse of density fluctuations in the early universe. In the early stages of cosmic evolution, matter was very dense and could be highly uneven on small scales, allowing matter in regions of extremely high density to directly collapse into black holes [3]. Additionally, mini black holes are also referred to as quantum black holes because quantum mechanics plays a significant role at this scale. In the near future, astrophysicists may be able to observe these black holes by detecting particles scattered due to the predicted Hawking radiation effect.

#### 4.1.2. Stellar-Mass Black Holes

Stellar-mass black holes have masses ranging from three to several hundred times that of the Sun and are typically formed by the direct collapse of large stars after their death. These black holes can be traced through gamma-ray bursts or supernovae and are believed to be widely present in the universe, with theoretical estimates suggesting at least hundreds of millions of stellar-mass black holes in the Milky Way. The continuous discovery of high-mass stellar black holes has forced scientists to re-examine the theories of stellar evolution leading to black holes and consider whether some mechanisms of black hole formation have been overlooked. The expansion of the upper mass limit of stellar black holes into the "forbidden zone" is pushing humanity to advance and explore this still mysterious field.

Traditional theories suggest that stars collapsing will not produce black holes with masses between 65 and 135 solar masses, defined as the forbidden zone. This mass forbidden zone is known as the pair instability mass gap.

#### 4.1.3. Intermediate-Mass Black Holes

Intermediate-mass black holes have masses ranging from a thousand to a hundred thousand times that of the Sun. Current research suggests that they originate from the absorption of a large amount of surrounding matter and the merger of several or more black holes. Although direct evidence has not

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been found, traces of them have been detected in three types of celestial systems. The first is the centers of globular clusters. The second is Ultraluminous X-ray sources (ULXs), which have a brightness exceeding $10^{39}$ erg/s (equivalent to an energy release greater than $10^{32}$ Joules per second—about 2 billion atomic bombs), far exceeding the brightness of typical galactic X-ray binaries, and are not located at the dynamic center of galaxies. The third, and currently the most promising for finding intermediate-mass black holes, is the centers of dwarf galaxies, where scientists have made the most progress.

#### 4.1.4. Supermassive Black Holes

Supermassive black holes can have masses ranging from tens of thousands to billions of times that of the Sun.

Observational evidence also indicates that almost all large galaxies have a supermassive black hole at their center [3]. Compared to black holes of relatively lower masses, supermassive black holes have some interesting differences: the average density of a supermassive black hole can be very low, even lower than the density of air. This is because the Schwarzschild radius is directly proportional to its mass, while density is inversely proportional to volume. Since the volume of a sphere is directly proportional to the cube of the radius, and mass increases almost linearly, the rate of volume increase is much greater. Therefore, density decreases with the increase in the radius of the black hole, and the tidal forces near the event horizon are significantly weaker.

### 4.2. Possible Formation Mechanisms

To form a black hole, an object must be compressed to an extremely high density. According to current speculation, there are three possible mechanisms for the formation of black holes. First, high-density media in the early universe, due to density fluctuations, can form black holes with a mass of about $10^{12}$ kg. Second, normal stars with a mass of a few to several tens of solar masses, evolving to a late stage, may collapse into a black hole under gravitational contraction. Third, supernovae, star clusters, or galactic nuclei can collapse under gravitational forces to form supermassive black holes with masses ranging from $10^4$ to $10^9$ solar masses [4]. Table 1 provides the necessity for stellar collapse to form black holes.

Table 1: Stellar Evolution Classified by Mass

| Stellar Class | Initial Mass ($M_\odot$) | Core Temperature (K) | Energy Source | Energy Loss | Death Cause | Final Stage | Pressure against Gravity |
|---|---|---|---|---|---|---|---|
| High Mass | > 8 | $3\times10^9 \sim 5\times10^9$ (Equilibrium) | Fusion of H, He, C, O, Si | Photons, Neutrinos | Gravitational Collapse | Black Hole | None |
| Medium Mass | 8 ~ 4 | $3\times10^9 \sim 7\times10^9$ (Explosion) | Fusion of H, He, C | Photons, Neutrinos | Supernova Explosion | Neutron Star | Neutron Degeneracy Pressure |
| Low Mass | 4 ~ 0.08 | $\sim 10^8$ | Fusion of H, He | Photons, Neutrinos (Negligible) | Mass Loss (Planetary Nebula) | White Dwarf | Electron Degeneracy Pressure |
| Very Low Mass | < 0.08 | $< 10^7$ | Gravitational Contraction | Photons, Neutrinos | Cooling | Red Dwarf | Electron Degeneracy Pressure |

## 5. Challenges in Cutting-Edge Black Hole Research

String theorists at the Kavi Theoretical Physics Institute at the University of California, Santa Barbara (UCSB), including Polchinski, have calculated results based on Hawking's "black hole evaporation theory" that differ from the predictions of general relativity. This result, published in July 2012, has shaken the physics community.

According to general relativity, an astronaut entering a black hole, even crossing the event horizon, would not feel much different, but over time, due to the inverse square law of gravity, he would gradually feel the gravitational pull on his head less than that on his feet. Moreover, this difference in gravitational force would increase rapidly, tearing him apart.

However, according to Polchinski, quantum effects would turn the event horizon into a fiery vortex of particles. Anyone falling into this vortex would hit a wall of fire and be instantly reduced to ashes [5].

The "fire wall" mentioned in their paper violates the cornerstone of physics established by Einstein about a century ago, which is the foundation of general relativity. Einstein's "equivalence principle" in his theory of gravity suggests that an observer falling into a gravitational field would see the same phenomena as an observer floating in a vacuum [5]. Without this principle, Einstein's theoretical framework would collapse.

However, if the conclusion is not pushed towards a fire wall, physicists would have to sacrifice another important pillar: quantum mechanics, a theory describing the interactions of subatomic particles.

Hawking's "black hole evaporation" theory is a milestone in the understanding of quantum effects in strong gravitational fields, but it also brings the black hole information paradox, that is, whether black holes satisfy the unitarity (conservation of information) of quantum mechanics during their formation and subsequent evaporation [3]. Scientists still need to deeply unify general relativity and quantum theory to truly solve the black hole information paradox.

## 6. Interesting Phenomena of Black Holes and Some of the Latest Research Findings

British scientists, after comparing the X-ray radiation from massive and small black holes, found that despite their varying sizes and masses, they have the same fluctuation patterns when absorbing surrounding gases and emitting X-rays. It is like singing the "same song" at different speeds but with the same pitch [1].

Recently, Tian Yu, a professor at the University of Chinese Academy of Sciences, and his Ph.D. student Chen Qian, in collaboration with researchers from Jinan University, Yangzhou University, and Shanghai Jiao Tong University, published a paper titled *Critical phenomena in dynamical scalarization of charged black holes in Physical Review Letters*. The study provides a physical process in which isolated black holes can continuously accrete scalar fields, transforming from hairless black holes to hairy black holes, providing a richer set of observable signals for gravitational wave detection and Event Horizon Telescope observations, making a significant contribution to the in-depth study of black hole physics [6].

## 7. Conclusion

This paper mainly discusses the development of the concept of black holes and their classification, and also mentions some cutting-edge achievements related to black holes. In summary, black holes are celestial bodies from which not even light can escape, and their existence can only be detected through indirect signals such as gravitational waves. There is still much to explore regarding the mechanisms of black holes. This paper does not discuss the more specific mathematical theories of

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black hole formation mechanisms. Readers can, after understanding the basic concepts of black holes, delve into their mathematical physics to gain a deeper understanding.

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