Proceedings of the 4th International Conference on Computing Innovation and Applied Physics
DOI: 10.54254/2753-8818/86/2025.20351

A Study of the Doppler Effect in the Analysis of Black Hole Images

Zheqi Tan[1,a,*]

[1]*China Hangzhou Shinyway Language, 310007, China*
a. 2050278634@qq.com
**corresponding author*

Abstract: Black holes, one of the most mysterious objects in the universe, have long captured the attention of the scientific community due to their extreme gravity and intricate physics. In theory, a black hole is formed when a massive star or object collapses at the end of its life cycle. When a star exhausts its core energy and is no longer acted upon by external forces, it begins to collapse inward. This process continues until the star reaches a critical density, at which point its gravity becomes so strong that not even light can escape, forming a black hole. Black holes exert a profound influence on the universe, continuously absorbing matter in their vicinity, including gas, dust, and other celestial objects. Focusing on the core physical properties and related phenomena of black holes, this paper explores the profound impact of black holes on existing physical theories. By analyzing the motion of matter and energy release mechanism under the gravitational field of black holes, it reveals the complex dynamic behavior of black holes under extreme conditions. In addition, it emphasizes the existence of singularities and their challenges to physics theories, especially the limitations of quantum gravity theory. The study of the Doppler effect and the relativistic beam effect provides further evidence of the high-speed motion of the matter around a black hole and the changes in its radiation properties. These in-depth discussions provide new perspectives for understanding the quantum properties of black holes and their importance in astronomy.

Keywords: Doppler Effect, Formation of Black Holes, Gravitational Lensing, Accumulation Disk Structures.

1. Introduction

Black holes are some of the most mysterious and powerful objects in the universe, with gravity so strong that not even light can escape. While Einstein's theory of general relativity predicted the existence of black holes as early as the early 20th century, it was not until 2019 that the first image of a black hole was released by the Event Horizon Telescope (EHT), which provided direct evidence for the theory. This image not only confirms the existence of black holes, but also clearly demonstrates their shadows and accretion disk features, further validating the validity of general relativity under extreme gravitational conditions [1]. Therefore, the paper delves into the nature of black holes, paying special attention to the redshift and blueshift phenomena, the relativistic beam effect, the formation and structure of the accretion disk, as well as the mode of matter motion and the jet stream phenomena exhibited in the black hole image. These phenomena elucidate the physical properties of black holes and furnish crucial insights into their impact on the surrounding milieu.

© 2025 The Authors. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/).

DOI: 10.54254/2753-8818/86/2025.20351

Specific studies include an investigation of the causes of redshift and blueshift phenomena observed in black hole images, an analysis of how the structure of the accretion disk affects the motion and radiation properties of the matter, and an examination of how the interaction between the black hole and the surrounding matter manifests itself through the relativistic beam effect. In addition, the study of black hole images and related phenomena is expected to deepen the understanding of black holes and provide a theoretical basis for future astrophysical research.

2. The Doppler Effect and the Basic Characteristics of Black Holes

2.1. The Gravitational Properties of Black Holes and the Event Horizons

Black holes are renowned for their immense gravitational pull, which renders even light incapable of escaping. When matter traverses the event horizon of a black hole (i.e., the boundary beyond which light cannot escape), it is inevitably consumed by the black hole. Figure 1 depicts the initial image of a black hole captured by the Event Horizon Telescope in 2019. The gravitational pull of a black hole is a consequence of the high concentration of its enormous mass within a relatively confined space. This phenomenon gives rise to a notable curvature of spacetime. In accordance with Einstein's theory of general relativity, the presence of mass gives rise to a curvature of the surrounding spacetime, which in turn exerts an influence on the trajectory of matter and light. In particular, the gravitational strength of a black hole grows exponentially with decreasing distance, making it impossible for matter and light in its vicinity to resist the powerful gravitational pull. The event horizon, a fundamental attribute of a black hole, is defined as a theoretical boundary. Once matter or light crosses the event horizon, it is unable to escape the gravitational confinement of the black hole. The radius of the event horizon (referred to as the Swashbuckler radius) is proportional to the mass of the black hole. Consequently, the greater the mass of the black hole, the greater the radius of its event horizon. Inside the event horizon, due to the extreme distortion of space-time caused by powerful gravitational forces, the traditional laws of physics no longer apply to this environment revealing phenomena very different from everyday experience.

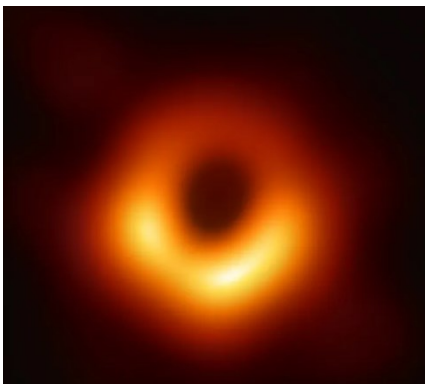


Figure 1: The First Black Hole Photographs Captured by the Event Horizon Telescope

2.2. The Existence of the Singularity

There exists a point at the center of a black hole called a singularity, characterized by a gravitational field of infinite density and strength. The inability of existing physical theories, especially general relativity, to adequately characterize this region poses a major challenge to modern physics. The formation of singularities arises from the evolutionary process of black holes. Toward the end of a star's life cycle, when a star's core runs out of nuclear energy and cannot resist its own gravity, the star undergoes gravitational collapse. This process causes matter to be compressed into a very small

DOI: 10.54254/2753-8818/86/2025.20351

volume, forming a singularity. In accordance with the tenets of general relativity, the appearance of a singularity is equivalent to asserting that the curvature of spacetime reaches infinity. This gives rise to the invalidation of the established laws of physics and the consequence of unpredictable behavior of matter and radiation in the vicinity of the singularity. Despite the incomplete elucidation of singularity properties, researchers are investigating their underlying physical mechanisms. For example, research in quantum gravity theory is attempting to combine quantum mechanics with general relativity to provide new insights into the behavior of singularities. These theoretical explorations aim to explain how matter exhibits anomalous properties under extreme gravitational fields and may reveal the relationship between singularities and phenomena such as the Big Bang and black hole evaporation. Therefore, studies targeting singularities are not only crucial for understanding the fundamental nature of black holes, but may also have a profound impact on the theoretical framework of cosmology as a whole. An in-depth research on singularities can provide new perspectives for our understanding of matter, space-time and their interactions [3].

2.3. The Definition and Application of the Doppler Effect

The Doppler effect is a phenomenon of frequency change caused by the relative motion between a wave source and an observer. When the wave source moves toward the observer, the frequency of the wave received by the observer increases, called the blue shift, while when the wave source moves away from the observer, the frequency decreases, called the red shift, as shown in Figure 2. This effect applies to sound and light waves, for example, the sound of an ambulance siren increases in frequency as it approaches and decreases as it moves away [2]. In astronomy, the Doppler effect is an important tool for studying the motion of celestial bodies. By analyzing changes in the frequency of light emitted by a celestial body, scientists can accurately measure its speed and direction relative to the Earth, which is especially important in the study of black holes. In particular, the capacity to discern redshift and blueshift phenomena through the observation of the spectral attributes of the matter in the vicinity of a black hole, thereby inferring the velocity and trajectory of this matter, is critical to comprehending the gravitational influence of black holes and their ramifications for the surrounding matter. Besides, the Doppler effect plays a key role in detecting gravitational interactions between black holes and other objects. As black holes and neighboring objects approach or move away from each other, the light waves they emit exhibit corresponding frequency changes. The accurate measurement of these variations can elucidate the dynamics of black holes in relation to other objects and their gravitational interactions.

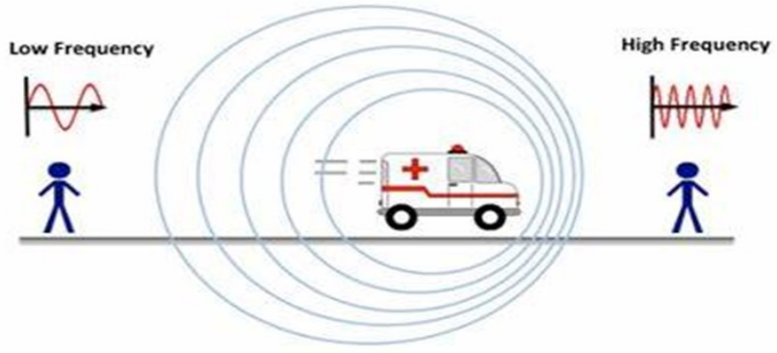


Figure 2: Doppler Effect for Redshift and Blueshift

DOI: 10.54254/2753-8818/86/2025.20351

3. The Motion of Matter Around Black Holes

3.1. The Formation and Structure of the Accretion Disk

As matter approaches a black hole, it is subject to the influence of the strong gravitational force, which causes it to form a ring-like structure known as an accretion disk. An accretion disk consists mainly of gas, dust and plasma, and its formation process is closely related to the angular momentum and gravitational interaction of matter. The accretion disk can be divided into an inner region and an outer region. The inner region is close to the black hole, where the matter moves at very high speeds and the temperature rises significantly, causing it to emit intense radiation, especially X-rays and gamma rays. These high-energy radiations are not only direct evidence of the black hole accretion process, but an important tool for us to study the physical properties of black holes. In comparison to the inner region, the outer region is distinguished by enhanced stability, diminished material movement, and diminished temperatures, which are primarily manifested in the absorption and re-radiation of radiation from the inner region. The differences in temperature and dynamics cause the accretion disk to exhibit a multifaceted physical environment in the different regions, affecting the material flow and energy transfer. The layered structure of the accretion disk and its dynamic evolution are of great scientific significance for understanding the gravitational effect of black holes, matter accretion, and its impact on surrounding objects [4].

3.2. Matter Motion Patterns and Jet Stream Phenomena

In an accretion disk, matter moves along a spiral orbit towards the center of the black hole. As the strength of the black hole gravity increases dramatically with decreasing distance, the matter in question accelerates continuously as it approaches the black hole. This acceleration causes the matter to exhibit a distinct pattern of spiral motion and also leads to a significant increase in temperature and energy. Inside the accretion disk, there is a constant loss of energy between the matter due to friction and turbulent interactions, which leads to a gradual increase in temperature. At the same time, these frictional interactions also lead to a gradual decrease in the angular momentum of the matter, bringing it closer to the black hole. In this process, the transformation of energy and the change of the state of matter form a complex dynamic equilibrium. In some cases, the matter around the black hole forms powerful jets that are ejected from the poles of the black hole. The creation of the jets is closely related to the magnetic field and rotation of the black hole. When matter falls into a black hole, the rotating magnetic field around it accelerates some of the matter to extremely high speeds, forming high-speed jets [5]. These jets, which are mainly composed of plasma, can be emitted outward at speeds close to the speed of light, significantly affecting the physical environment of the surrounding space. Figure 3 shows the energy distribution and location of the jets, further illustrating the relationship between the jet phenomenon and the motion of matter inside the accretion disk.

DOI: 10.54254/2753-8818/86/2025.20351

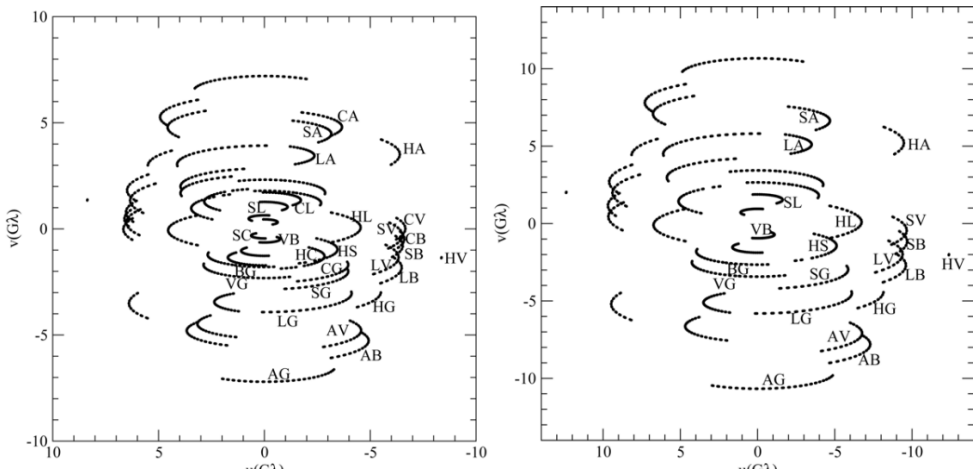


Figure 3: Energy Distribution and Location of Jets

4. Redshift and Blueshift Phenomena in Black Holes

4.1. Relativistic Beam Effect

The relativistic beam effect is produced by matter spinning at high speeds around a black hole, due to the near-light speed motion of the particles involved. This phenomenon is particularly discernible in environments that are highly extreme, particularly in accretion disks and black hole jets. According to the relativistic effect, when matter is moving near the speed of light toward the observer, the radiation is concentrated in a narrow region of the observer's field of view, resulting in a significant increase in the intensity of the observed radiation, creating the so-called blueshift phenomenon. In contrast, matter moving away from the observer exhibits a redshift phenomenon, where the wavelength of its radiation is elongated and its frequency is reduced. The relativistic beam effect is important for the study of the radiative properties of black holes, as it allows for the revelation of the extreme physical conditions that prevail in the matter that surrounds them. In particular, it can provide crucial information when the dynamical behavior of accretion disks and jets is being analyzed.

4.2. Energy Distribution Analysis

The energy distribution around a black hole is the basis for the formation of redshift and blueshift phenomena. Matter in the inner regions of the accretion disk acquires extremely high kinetic energy due to the rapid decrease in gravitational potential energy and drastic changes in angular momentum. Matter in these regions moves at speeds close to the speed of light, producing high-frequency radiation and forming the blueshift effect. In contrast, the matter in the outer regions moves slower due to the weaker gravitational effect of the black hole, and the frequency of radiation decreases, forming a redshift phenomenon. By analyzing the energy distribution in black hole images, scientists can infer the trajectory, speed distribution, and energy release patterns of matter in different regions. The redshift and blueshift effects can provide information about the dynamics of matter in the vicinity of the black hole, as well as reveal the strength of its magnetic field, the process of matter accretion, and the acceleration mechanism of the jet stream. And as shown in Figure 4, the energy destruction at each position is entirely distinct, which is the relativistic bundle effect [6].

DOI: 10.54254/2753-8818/86/2025.20351

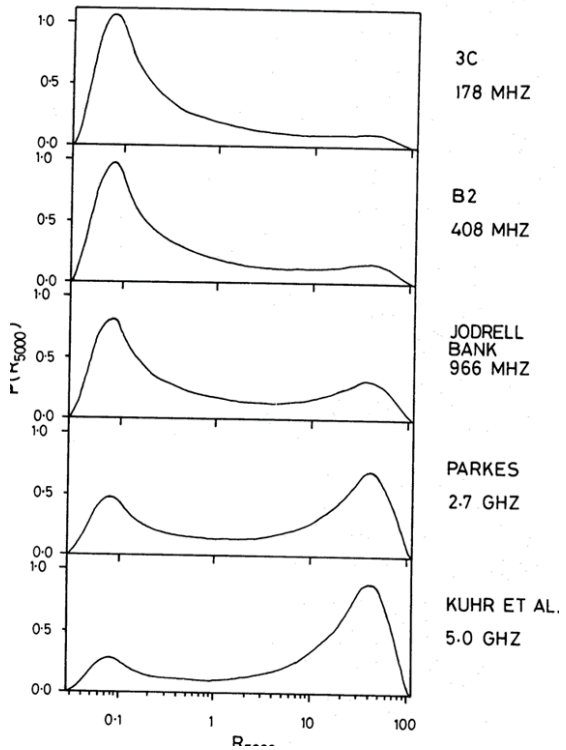


Figure 4: The Intensity of Energy Destruction

5. Technical Challenges and Future Outlook

The study of black holes presents a number of technical challenges, the first of which is the integration of quantum gravity theory and general relativity. First, in the extreme environment of black holes, the contradiction between quantum mechanics and the theory of gravity becomes more and more obvious, which makes black holes an ideal object for the study of quantum gravity. Current research is devoted to constructing a more comprehensive theory of quantum gravity, aiming to explain key issues such as the nature of singularities inside black holes and information paradoxes, and current research directions such as string theory and loop quantum gravity theory may provide new perspectives to this end. In addition, the investigation of the interconnection between black holes and dark matter is becoming a crucial area of research. Primordial black holes are regarded as potential candidates for dark matter. Thus, a comprehensive investigation of their formation processes and interactions with dark matter is crucial for elucidating the nature of dark matter and its influence on the evolution of the universe. This requires collaborative interdisciplinary research in the fields of high-energy physics, cosmology and astrophysics. Finally, although the Event Horizon Telescope (EHT) has successfully captured images of black holes, its resolution is still limited, making it difficult to reveal the detailed structure of the matter inside and around black holes. Improvements in imaging accuracy urgently require technological innovations, including improvements in radio telescopes, development of high-frequency observing techniques, and optimization of data processing algorithms. The Next Generation Event Horizon Telescope program was developed to address these issues, but it will encounter several obstacles in its implementation, including the complexity of large-scale collaborations, the difficulty of accurate calibration, and the need for increased data-processing power. The overcoming of these technical hurdles may facilitate a more profound investigation of the enigmas of black holes and their function within the cosmos [7].

DOI: 10.54254/2753-8818/86/2025.20351

6. Conclusion

As the most mysterious and extreme objects in the universe, the properties and behaviors of black holes occupy an important position in physics research. By analyzing the Doppler effect, this paper reveals the motion patterns of the matter surrounding black holes and their effects on the radiation properties, thus enabling the taking of images of black holes. These images not only provide direct evidence of the existence of black holes, but also further validate the relevant physical theories and promote a deeper understanding of the internal structure and behavior of black holes. However, there are some limitations in the study, which mainly focuses on the exploration of the Doppler effect and fails to fully analyze the gravitational lensing effect and the relativistic beam effect. In addition, the current observational techniques limit the fine observation of the matter around black holes, which affects the comprehensiveness and accuracy of the data. Future research should employ a combination of observational techniques and utilize advanced observational tools, particularly the development of new-generation radio telescopes, to gain a more comprehensive understanding of black hole properties. Meanwhile, further exploration of the relationship between black holes and dark matter and quantum gravity theories is expected to answer deep questions about the evolution of the universe, thus revealing more mysteries about black holes and their role in the universe.

References

[1] *Lu, R., Broderick, A.E., et al. (2014) Imaging the supermassive black hole shadow and jet base of M87 with the event horizon telescope. The Astrophysical Journal, 788(2): 120.*

[2] *Neipp C, Hernández A, Rodes J J, et al. An analysis of the classical Doppler effect[J]. European journal of physics, 2003, 24(5): 497.*

[3] *Poisson, E. and Israel, W. (1990) Internal structure of black holes. Physical review. D, Particles and fields, 41(6): 1796-1809.*

[4] *Lu, J.F. (2001) Progress in the theory of black hole accretion disks. Progress in Astronomy, 19(3): 365-374*

[5] *Parfrey, K., Philippov, A. and Cerutti, B. (2018) First-Principles Plasma Simulations of Black-Hole Jet Launching. Physical review letters, 122(3)L 035101 .*

[6] *Barbier, H. and López, E. (2021) Kepler Planetary Systems: Doppler Beaming Effect Significance. Revista Mexicana de Astronomía y Astrofísica, 57(1): 123-132.*

[7] *McCrea, W.H. (1972) Relativistic Beaming. Monthly Notices of the Royal Astronomical Society, 157(4): 359-365.*