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# BLACK HOLES

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**ABSTRACT**

This paper explores the physical and dynamic characteristics of black holes, providing a detailed overview of the formation mechanisms for different categories of black holes and their potential evolution over time. The study examines black hole theory from the perspective of classical gravitational theory, as formulated by Isaac Newton, as well as from the framework of Albert Einstein's theory of general relativity.

Furthermore, the role of a quantum theory of gravity, also known as quantum gravity, is discussed. This theoretical framework aims to unify general relativity and quantum mechanics, offering a deeper understanding of black hole phenomena, particularly the central region known as the "singularity."

**Key words:** space, time, mass, gravity, singularity

## Introduction

Black holes are among the most bizarre and fascinating celestial objects in the Universe. They possess a gravity so strong that not even light can escape from it. As a result, we cannot observe them directly through telescopes. However, we can infer their presence and study them based on the gravitational effect they have on surrounding objects. Their existence was predicted by Albert Einstein's theory of general relativity in 1915. Yet, the first black hole was only detected in 1964 by X-ray detectors installed on a suborbital rocket. This black hole was named Cygnus X-1. Cygnus X-1 has a mass equivalent to 21 solar masses. It is part of a binary star system, orbiting around the common center of mass together with a blue supergiant star, which has a mass equivalent to 41 solar masses, with an orbital period of 5.6 Earth days. This binary star system is located at a distance of 7,200 light-years from Earth. Since it is a close binary star system, the matter from the outer layers of the blue supergiant star is absorbed by the black hole. As it falls into the black hole, it heats up immensely, thus emitting X-rays and gamma rays.

## Material and method

According to the theory of general relativity, our Universe is a hypersurface on which all celestial bodies move, representing the space-time structure. The space-time structure isn't entirely rigid; its geometry is deformed by the presence of mass and energy, causing it to curve. This curvature of the space-time structure "creates" what classical physics calls "gravity." The theory of general relativity posits that two celestial bodies orbit around their common center of mass or one falls onto the other not due to a distant force of gravitational attraction between the two bodies, but because the space-time structure is curved by the masses of the two bodies. This curvature is greater the larger the body's mass, so the smaller body ends up orbiting around or falling onto the larger body simply by traveling the curved shape of the space-time structure around the larger body.

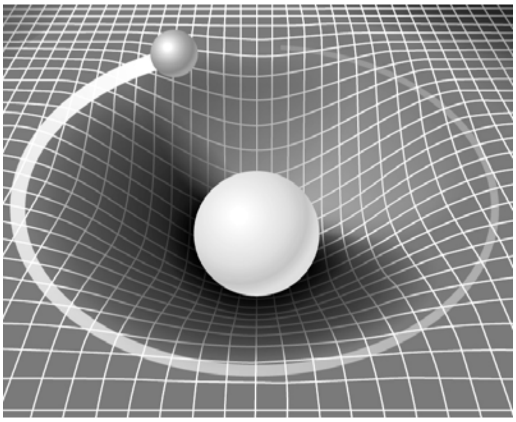

**Fig. 1** - general relativity treats gravity not as a force, but as the consequence of movement of bodies in curved space-time structure

A black hole is a spherical region of the Universe where the space-time curvature is so high that all bodies near it are "driven" to its center. The distance from the center of a black hole from which

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light can no longer escape its gravity is called the Schwarzschild radius. For instance, for a black hole whose mass is equivalent to the Sun's, the Schwarzschild radius would be about 2.9 km, and that's for a non-rotating black hole. The sphere that surrounds a black hole and has a radius equal to the Schwarzschild radius is called the event horizon. If you've penetrated within this sphere, it's impossible to escape the black hole's gravity! Current theories suggest that the inside of this sphere is empty, with the entire mass of the black hole concentrated at the central point where the curvature of space-time structure is infinite, termed the "singularity." Up until now, no direct measurement has been made within the event horizon of any black hole. Before reaching the event horizon, we encounter the photon sphere, where photons orbit around the black hole!

While a black hole is defined as a celestial object with gravity so strong that not even light can escape it, this only holds true at close distances to the black hole. At vast distances, on the order of astronomical distances, the difference between the gravity of a black hole and the gravity of a star with mass equal to that of the black hole is imperceptible! However, as distances decrease, this difference becomes increasingly pronounced!

If a person were to fall into a stellar black hole, the gravity at their feet would be much stronger than at their head, resulting in them being stretched out and torn apart as they fall into the black hole, a phenomenon termed "spaghettification".

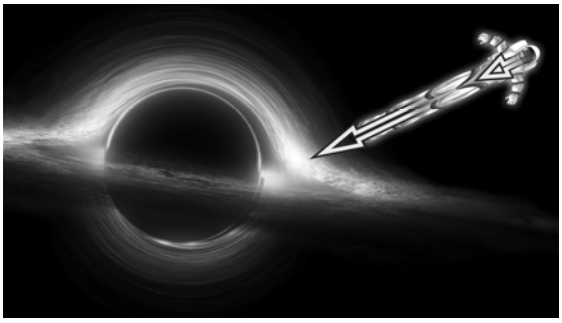

**Fig. 2** - ”Spaghettification”

Up to now, astronomers have identified three types of black holes: stellar black holes, intermediate black holes, and supermassive black holes. However, the majority of detected black holes are either stellar or supermassive.

Stellar black holes are either produced through a supernova or a kilonova. When a star exhausts its nuclear fuel, the star's core collapses, and its outer layers are expelled into space, forming a nebula. In the case of massive stars, this occurs through an extremely violent explosion called a supernova. If the star's core mass is less than 1.4 solar masses, it will collapse into a white dwarf star (with a density on the order of $1x10^9$ kg/m$^3$); if the star's core mass is between 1.4 and 3 solar masses, the star will explode in a supernova, and its core will collapse into a neutron star (with a density on the order of $2x10^{26}$ km/m$^3$). If the star's core mass exceeds 3 solar masses, following the supernova explosion, the core will collapse into a black hole. The second method for the formation of black holes is kilonovae, explosions resulting from the collision and merging of two neutron stars.

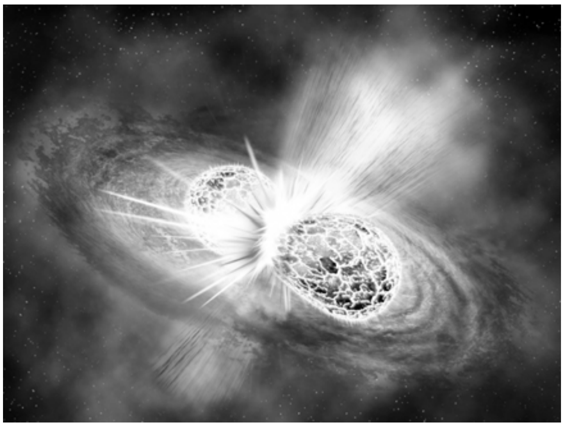

**Fig. 3** - Kilonova

The majority of stellar black holes have masses up to 100 times greater than the mass of the Sun, while supermassive black holes have masses starting at 1 million solar masses and can even reach values of billions of solar masses. Supermassive black holes have been discovered in the centers of large galaxies and can be detected due to the gravitational influence they exert on nearby stars and nebulae. Our own galaxy, the Milky Way, houses a supermassive black hole at its core with a mass of over 4 million solar masses. While for a black hole with a mass equal to the Sun, the Schwarzschild radius is nearly 3 km, for the supermassive black hole at the center of the Milky Way, the Schwarzschild radius is 12 million kilometers! If a star gets too close to the supermassive black hole, the extremely strong tidal effect caused by it can significantly deform the star, stripping matter from its outer layers. This matter then begins to spiral down into the black hole, forming an accretion disk around it. The intense friction within the disk heats the matter to millions of degrees Celsius, emitting electromagnetic radiation in the X-ray and gamma-ray spectrum. Towards the central area of the accretion disk, the speed of the matter becomes extremely high, and the magnetic field is immensely strong. As a result, although most of the matter from the accretion disk falls into the supermassive black hole, some particles are accelerated to speeds close to the speed of light and expelled in two relativistic plasma jets along the black hole's rotational axis. These are also high-energy radiation sources. Ironically, while we can't directly see the black hole itself, the space around it can be incredibly bright if the black hole is being fed with matter!

**Fig. 4** - Accretion disk around a black hole

While the number of stellar and supermassive black holes detected so far is large, the number of intermediate-mass black holes is, however, very low. Intermediate-mass black holes might form from the growth of stellar black holes, either by merging with other stellar black holes or by "feeding" on the surrounding matter. Alternatively, they could form within globular star clusters due to cascading collisions between stars, with the product of these collisions collapsing to form these intermediate-mass black holes. Such intermediate black holes have been found primarily in densely populated globular star clusters located in the central regions of small to medium-sized galaxies.

If two black holes orbit around each other, their gravitational interaction creates "waves" in the fabric of space-time. These spread outward as gravitational waves, a prediction of the theory of relativity. Such gravitational waves were first detected on September 14, 2015, by the detectors of the American LIGO Observatory (Laser Interferometer Gravitational-wave Observatory). The signal captured by LIGO's detectors was produced by the collision of two black holes, one with a mass equivalent to 29 solar masses and the other with 36 solar masses. This event occurred 1.3 billion years ago. According to the theory of general relativity, two black holes orbiting each other lose energy by emitting gravitational waves, so over time they come closer to each other until they eventually collide. The speed at which they collide is immense, almost half the speed of light. After the merger, a more massive black hole is formed. Part of the combined mass of the initial two black holes is converted into energy, according to Einstein's formula $E=mc^2$. In the case of the collision detected on September 14, 2015, out of the combined mass of the two black holes, which was 65 solar masses, about 3 solar masses were converted in a fraction of a second into gravitational waves. These waves were captured by LIGO's detectors. This discovery came 100 years after Albert Einstein predicted their existence in his theory of general relativity. The three astrophysicists who made this discovery, Kip Thorne, Barry Barish, and Rainer Weiss, won the Nobel Prize in Physics in 2017.

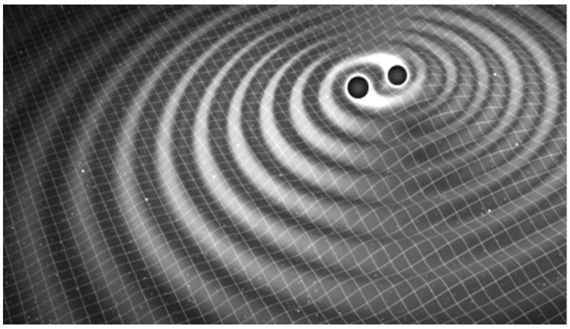

**Fig. 5** - Gravitational waves produced by the collision of two black holes

According to astrophysicist Stephen Hawking, black holes evaporate over time through a process called "Hawking radiation". According to quantum mechanics, the vacuum is not truly empty; it is a sea of virtual particles that appear in particle-antiparticle pairs for a very short time and then disappear. Stephen Hawking proposed that if a pair of virtual particles forms near a black hole, say, for example, an electron and its antiparticle, the positron, there's a possibility that one of the two particles is absorbed by the black hole. Consequently, the other one, left alone and not quickly annihilated, transitions from being a virtual particle to a real particle, escaping into space. The energy required for this process comes from the black hole itself, causing it to lose energy, or in other words, "evaporate". However, calculations show that this evaporation process is very slow: a stellar black hole with a mass 10 times greater than the Sun's mass would take $10^{65}$ years to evaporate, while a supermassive black hole with a mass 1 million times greater than the Sun's would take $10^{80}$ years. These time spans are much longer than the current age of the Universe!

## Results and discussions

A black hole is a great amount of matter packed into a very small area. The result is a gravitational field so strong that nothing, not even light, can escape. Astronomers can detect them by watching for their effects on nearby stars and gas. Black holes are one of the most extreme environments humans are aware of, and so they are testing ground for the laws of physics and our understanding of how the Universe works.

## Conclusions

To fully understand the nature of a black hole, especially the region termed its "singularity", a quantum theory of gravity is required. This theory, also known as quantum gravity, would combine general relativity with quantum mechanics. It remains one of the major challenges in modern theoretical physics.

## Rezumat

Lucrarea de față prezintă caracteristicile fizice și dinamice ale găurilor negre. Este prezentat modul în care se formează diferitele categorii de găuri negre, precum și modul în care acestea pot evolua în timp. Este abordată teoria găurilor negre atât din punctul de vedere al teoriei clasice a gravitației a lui Isaac Newton, cât și din perspectiva teoriei relativității formulată de Albert Einstein. O teorie cuantică a gravitației, cunoscută și sub numele de gravitație cuantică, teorie care ar combina teoria relativității generalizate cu mecanica cuantică, va contribui la înțelegerea deplină a ce înseamnă o gaură neagră și în special regiunea numită „singularitate” a acesteia.

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