

# Stephen Hawking: Black Holes and other Contributions from one of the Greatest Scientists of Our Time

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**Abstract**— *Stephen Hawking entered the hall of the greatest scientists of all time, alongside names like Galileo, Newton and Einstein. He was a warrior fighting a degenerative disease that deprived him of movement. Hawking made important contributions to understanding the functioning of the Universe by exploring issues such as Black Holes, Wormholes, Space and Time, and the Big Bang. The understanding of the Thermodynamics of the Black Holes caused us to approach the Relativity of Quantum Mechanics, leaving the "Theory of Everything" closer to our reality. Stephen William Hawking was born exactly on the 300<sup>th</sup> anniversary of Galileo's death and died at the age of 76 on Albert Einstein's birthday on Pi Day on March 14, 2018.*

**Keywords**— *Hawking, Universe, Black Holes, Big Bang.*

## I. INTRODUCTION

Stephen William Hawking was a British physicist and cosmologist and one of the most renowned scientists of today. He was born exactly on the 300<sup>th</sup> anniversary of Galileo's death and died, to the 76 years, on Albert Einstein's anniversary of the birth, on the Pi Day, on March 14, 2018.

He entered Oxford in 1959, where he intended to study mathematics, but since the course was not available at that university, he chose to study physics, graduating three years later. His main interests were quantum mechanics, thermodynamics and relativity. After obtaining his doctorate at Trinity Hall in Cambridge in 1966, he became a researcher and later a professor at Gonville and Caius College.

After leaving the Institute of Astronomy in the year of 1973, Stephen entered the Department of Applied Mathematics and Theoretical Physics having occupied the

position of Mathematics professor, chair that outside of Sir Isaac Newton and Paul Dirac, having been Emeritus professor of the University of Cambridge.

Hawking is widely known for his work on quantum physics, especially with regard to the origin of the universe.

Due to his constant preoccupation in exposing the complex astrophysical theories to a lay public through several books of scientific diffusion, it has become quite famous.

## II. THE STEPHEN HAWKING CONTRIBUTIONS

After a lecture given by the brilliant British physicist and mathematician Roger Penrose, Stephen Hawking extended the concepts of the singularity theorem exposed by Penrose, which he had explored in his doctoral thesis.

The innovation of the Stephen Hawking's approach lies in how he demonstrated the concept of uniqueness in physics, which includes not only the existence of singularities but also the theory that the universe may have started as a singularity, that is, a single event.

Hawking and Penrose published in 1970 a study that demonstrates that the universe obeys the theory of general relativity and that this is valid for any model of physical cosmology developed by Alexander Friedmann. In this study they develop the idea that the universe must have begun as a singularity usually dubbed "Big Bang".

Penrose-Hawking singularity theorems are a set of results in general relativity, which deal with the question of gravity to be singular. In a physical theory of gravitation, a singularity can be considered as a point in spacetime where various physical quantities, such as

curvature or energy density, become infinite, causing physical laws to be "broken."

An interesting "philosophical" aspect of general relativity is revealed by the theorems of singularity. Because general relativity predicts the inevitable occurrence of singularities, theory, in a certain respect, predicts its own ending in a finite time in the future.

### STEPHEN HAWKING AND THE BLACK HOLES

After working with Penrose, Hawking discovered what became known as the second law of black hole dynamics. According to this law the event horizon of a black hole never gets smaller even if its mass is reduced. Together with James M. Bardeen and Brandon Carter, he proposed the four laws of black hole mechanics, making an analogy with thermodynamics. Although his theory of black holes had aroused a great interest quickly in the scientific community, it needed to be corrected in several points.

Hawking began noticing by astronomical calculations and scrutiny that some results contradicted his Black Hole Second Law, where he stated that the black hole event horizon could never diminish. In conjunction with this and in cooperation with Russian physicists he described in 1974 a kind of radiation that black holes emit that explained the apparent contradictions in his earlier observations, his discovery was christened in his tribute as Hawking Radiation.

Stephen Hawking proposed in 1981 that the information that is engulfed by a black hole is hopelessly lost when a black hole collapses. This statement led to a paradox that violates the fundamental principle of quantum mechanics. This triggered a heated debate between Stephen Hawking, Leonard Susskind and Gerard 't Hooft, who became known as the "Black Hole War." That same year, at a conference in the Vatican, he presented his work suggesting that "there may be no limit to the beginning or end of the universe." Working together with Jim Hartle two years later, he proposed a model known as the Hartle-Hawking State. According to this model the universe had no space-time limit before the Big Bang, that is, time did not exist and the concept of the beginning of the universe is meaningless. This greatly altered his initial idea based on the concept of singularity of the general relativity theory, replacing the classic Big Bang model with a model that can be explained by the following analogy: *"Consider that a person intends to travel to the North Pole, and begins to walk toward it. However, there is no specific boundary that determines whether or not it has reached the North Pole. The North Pole is not simply the point where all the lines that follow north come to an end."*

### III. BLACK HOLES

A classic black hole is an object with a gravitational field so intense that the escape velocity exceeds the light speed, that is, not even the light can escape from its interior, even traveling at 299,792,458 m/s. The term "black" is used exactly because the object does not emit light. By attracting everything around it and not being seen (it does not emit light), it is as if there were a "hole" that worked like a large "drain". Hence the term "Black Hole".

This expression was first used by American physicist John Archibald Wheeler in an important article called "The Known and the Unknown," published in American Scholar and American Scientist in 1968. A black hole can theoretically have any size. Thus there is the possibility of Black Holes with sizes ranging from microscopic to light-days in diameter, formed by fusions of several others.

Black holes have only three characteristics: mass, angular momentum (spin) and electric charge, that is, black holes with these three equal quantities are indistinguishable in the same way that electrons possessing the same properties cannot be distinguished. There is a well-known phrase among cosmologists, which applies precisely because of this property: "a black hole has no hair."

After its formation its mass increases due to the attraction of other bodies, and its size tends to zero, due to the action of its gigantic gravitational field, causing its density to tend to infinity. Black holes, like other objects whose gravitational pull is extreme, slow time due to gravitational effects. Black holes cause a space-time distortion, related to the gravitational lens effect.

### IV. ESCAPE VELOCITY AND THE "SCHWARZSCHILD RADIUS" (RS)

The escape velocity of an object is the speed that it must attain to escape the gravitational pull of a body.

The mechanical energy ( $E_m$ ) is the sum of the kinetic energies ( $E_c$ ) and potential ( $E_p$ ):

$$E_m = E_c + E_p$$

In order that the body escape from the gravitational field, it must reach infinity, where the mechanical energy is zero ( $E_m = 0$ )

Thus

$$0 = \frac{1}{2}mV_e^2 - \frac{GMm}{r}$$

Applying this concept to the black hole, ie where the escape velocity ( $V_e$ ) is at least equal to the light velocity ( $c$ ), we have:

$$0 = \frac{1}{2}mc^2 - \frac{GMm}{r}$$
$$r = \frac{2GM}{c^2} = r_s$$

$r_s$  : Schwarzschild ray

$G$  : gravitational constant, which is  $6.67 \times 10^{-11} \text{ N m}^2/\text{kg}^2$ ;

$m$  : mass of the object;

$c^2$  : speed of light squared =  $8.98755 \times 10^{16} \text{ m}^2/\text{s}^2$ .

This radius is known as the "Schwarzschild Ray" ( $r_s$ ) and is associated with the extent of the event horizon that would exist if the mass of a body were concentrated in a single point of infinitesimal dimensions. The term, which is widely used in the gravitation theory in general relativity, was discovered in 1916 by Karl Schwarzschild. It does not give the exact solution to the gravitational field of a spherically symmetrical star (Schwarzschild Geometry), which is a solution of Einstein's field equations.

An object smaller than its Schwarzschild radius is called a black hole, since its density is such that the escape velocity is greater than that of light. The sphere surface defined by the Schwarzschild radius acts as an event horizon in a static body. Neither light nor particles can escape the interior of Schwarzschild beam, hence the name "black hole."

The Sun has a Schwarzschild radius of approximately 3 km, and the Earth approximately 9 mm. The Schwarzschild radius of the supermassive black hole at the center of our galaxy is approximately 7.8 million kilometers.

## V. ENTROPY

Entropy ( $S$ ) is the measure of the degree of disorder of a system and it tends to increase naturally in the Universe. It is related to the Second Law of Thermodynamics.

We can, for example, observe the ice that melts. The molecules in the solid state are closer and have less possibility of movement, therefore they are more organized. By moving to the liquid state, molecules gain more and more freedom to move and with this they will become increasingly disorganized. These changes in physical state are related to energy in the form of heat.

Thus, the natural tendency is to increase the disorder of molecules, which means an increase in entropy. We can say then that in systems:  $\Delta S > 0$ .

The concept of Entropy began with the French engineer and researcher Nicholas Sadi Carnot. In his research on transformations from mechanical to thermal energy, and vice versa, he found that it would be impossible for a machine to exist with full efficiency, that is, there is no physical possibility of the existence of a machine with 100% efficiency.

The First Law of Thermodynamics states that "energy is conserved." This means that in physical processes the energy is not lost, it converts from one type to another. Analyzing only this Law, we could assume the

existence of a machine with 100% efficiency. The second law forbids this.

When a machine uses energy to do the work, in this process the machine heats up, that is, there is a part of the mechanical energy being degraded in the form of thermal energy. This thermal energy does not fully transform back into mechanical energy, so the process is irreversible. If we could reverse the process, the machine would never stop working.

Later the British mathematician and physicist William Thomson, Lord Kelvin, complemented Carnot's research on the irreversibility of thermodynamic processes, giving rise to the foundations of the Second Law of Thermodynamics.

The second law of thermodynamics concisely expresses that "the amount of entropy of any thermodynamically isolated system tends to increase with time until it reaches a maximum value." "It is impossible to construct a device which, by itself, that is, without intervention from the external environment, can transform the heat absorbed from a source at a given uniform temperature into work" (Kelvin-Planck's statement).

Rudolf Clausius was the first to use the term "Entropy" in 1865. Entropy would be the measure of the amount of thermal energy that cannot be reversed in mechanical energy, ie, it cannot perform work, at a certain temperature.

Clausius developed the mathematical formula for the entropy variation that is currently used:

$$\Delta S = \frac{Q}{T}$$

$\Delta S$ : Entropy variation

$Q$ : Heat transferred

$T$ : Temperature.

## VI. HAWKING AND THE BLACK HOLE ENTROPY

The existence of Black Holes was proposed from the General Theory of Relativity. In 1974, Hawking proposed that in the event horizon, particles would escape like radiation what was known as Hawking radiation. Thus, the black hole should slowly evaporate until it disappears, making it obey the Second Law of Thermodynamics - which predicts that the entropy of a system could never diminish. If the hole only engulfed matter without giving back anything, the entropy of the Universe would be compromised.

Entropy is a measure that characterizes the number of internal states of a black hole. The Black Hole entropy formula was developed in 1974 by British physicist Stephen Hawking.

If black holes did not have entropy, we could violate the Second Law of Thermodynamics by throwing mass into a black hole. The only way to satisfy the second

law is to admit that Black Holes have entropy whose increase more than compensates for the decrease in entropy associated to the object that has been swallowed.

Through the Stephen Hawking theorems, Mexican physicist Jacob Bekenstein conjectured that the black hole entropy was proportional to the area of its event horizon divided by the Planck area.

Later, Stephen Hawking showed that black holes emit Hawking thermal radiation corresponding to the certain temperature, known as Hawking temperature. Using the thermodynamic relationship between energy, temperature and entropy, Hawking was able to confirm the Bekenstein conjecture and fix the proportionality constant in  $\frac{1}{4}$ .

$$S = \frac{Akc^3}{4\hbar G}$$

S: Entropy

A: The area

k: Boltzmann constant

$\hbar$ : Normalized Planck constant

G: Newton Universal Gravitational constant

c: Speed of light in a vacuum

The black hole entropy is also the maximum entropy that can be inserted within a fixed volume.

If nothing can surpass the light speed, according to the German physicist Albert Einstein Restricted Relativity Theory, nothing can escape the gravity of a Black Hole.

There is a possibility that the event horizon is a measure of the Entropy of a Black Hole. By the Werner Heisenberg Uncertainty Principle there is no absolute vacuum. There are, then, several pairs of virtual particles (particles and antiparticles) interacting with each other around a Black Hole, in which the positive energy of one particle cancels out the negative energy of the other, and vice versa. The antiparticle would be drawn to the very strong gravity of the Black Hole and would fall into it, freeing its partner of positive energy into outer space.

The negative energy of the antiparticle inside the Black Hole would diminish part of its mass, since it would cancel part of the positive energy of the Black Hole mass. The released particle, for a distant observer in space, would seem to have been emitted by the Black Hole. Thus, this particle would not come directly from the Black Hole, as thought by the external observer, but from the outer space itself, through the "creation of pairs", thus making the Event Horizon be considered as a measure of the Entropy of a Black Hole. This radiation "emitted" by a Black Hole is called Hawking Radiation.

## VII. FIREWOOD IN THE BONFIRE - EVENTS HORIZON

Stephen Hawking, one of the creators of modern black hole theory, has published an online article recently, still unreviewed by other scientists, stating "There are no black holes."

The statement puts more fire in the discussion that attempts to reconcile the relativity theory (which explains the macroscopic world) with quantum mechanics (which explains the microscopic world).

The report of the scientific journal Nature, which commented the new study by Hawking, recalls that the proposal of the radiation generated other doubts, among them what was known as paradox of the wall of fire.

By quantum mechanics, Hawking radiation would not simply dissipate, but would form a "wall of fire" around the event horizon. The problem is that it can not be one thing or another. Although scientists do not yet know how, for the world to work, the two theories (Quantum and Relativity) have to talk. Hawking proposed now, in an article on ArXiv website, that instead of an event horizon, there would be an "apparent horizon," a surface that can capture light, but it can also change shape due to quantum fluctuations, exhaust.

"The absence of an event horizon means that there are no black holes in the sense of systems from which light cannot escape into infinity," Hawking wrote in the article.

In an interview with Nature, Hawking says: "There is no escape for a black hole in classical theory." However, Quantum Mechanics "allows energy and information to escape from a black hole." To definitively solve the problem, only unifying the theories, he says. This problem has intrigued scientists for nearly a century. Thus, "the correct explanation remains a mystery."

## VIII. FINAL CONSIDERATIONS

Stephen Hawking entered the hall of the greatest scientists of all time, alongside names like Galileo, Newton and Einstein. He was a warrior fighting a degenerative disease that deprived him of movement.

Hawking made important contributions to understanding the functioning of the Universe by exploring issues such as Black Holes, Wormholes, Space and Time, and the Big Bang.

The biggest challenge in detecting a black hole would be to be able to observe it if, by its very definition, it does not emit any light. In 1783, John Michell pointed out in his pioneering work that a black hole exerts gravitational force on nearby objects.

The understanding of the Thermodynamics of the Black Holes caused us to connect the Relativity and

Quantum Mechanics Theories, becoming the "Theory of Everything" closer to our reality.

Scientists suspect that most galaxies have black holes in their center, which are fed with gases, dust and stars around them. Sometimes black holes release enough energy to prevent star formation. The way stars and black holes evolve together, however, remains a mystery to scientists. The hope is that data from existing modern telescopes will enable new discoveries in this field. Thus, the number of black holes is probably much larger than imagined; which may be much larger than that of visible stars, which amount to about one hundred billion, only in our galaxy.

But, in fact, there are many mysteries surrounding the black holes that science has not yet been able to discover. For example, do they represent a passage to other universes, and allow intergalactic journeys? That would be very interesting, but for now it's just fiction, it's just imagination. We still need a lot of mathematics, physics and astronomy to understand the reality that is associated with black holes.

To paraphrase Ann Druyan, in his farewell to Carl Sagan, we can say, without resorting to mysticism that Hawking went to Heaven.

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