NOBEL PRIZE IN PHYSICS 2020

(December 2020)

On October 6^{th}, 2020 the general secretary of the Royal Swedish Academy of Science announced that the English Roger Penrose has been laureated with the Physics Nobel Prize of 2020 for finding that the black hole formation is a robust prediction of the General Relativity Theory. The prize is shared with the German Reinhard Genzel and Andrea Ghez from the United States for the discovery of a supermassive compact object in the center of our galaxy. Sir Roger Penrose is 89 years old and is an emeritus Rouse Ball math professor at Oxford University. He has received several prizes and awards as the Wolf Award in Physics in 1988, which was shared with Stephen Hawking, for their joint contribution to our comprehension of the universe. Professor Penrose is a mathematician, Ph.D. in Cambridge in 1958 with a thesis about tensorial methods in algebraic geometry, but he is a universal thinker, recognized, particularly, for his contributions to General Relativity and Cosmology.

Reinhard Genzel is 68 years old and is a scientific member of the Max Plank Society and director of Max Plank Institute of Extraterrestrial Physics in Garching, Germany; he also is titular professor at the University of California, Berkeley, USA. Professor Genzel won the Albert Einstein Medal, among other important distinctions. He studied Physics at the University of Friburgo and at the University of Bonn where he had his Ph.D. in 1978 and, in the same year, his doctoral thesis about radio astronomy at the Max Plank Institute of Radio astronomy.

Andrea Mia Ghez is 55 years old, she is professor at the Physics and Astronomy Department at the University of California in Los Angeles, USA. She has received several awards and distinctions, one of them being the Gold Shield Alumnae of UCLA. She is the fourth woman that wins the Physics Nobel Prize. She obtained her bachelor's degree in Physics at the Massachusetts Institute of Technology in 1987 and the Ph.D. at the California Institute of Technology in 1992. Professor Ghez is known for the use of adaptive optics in research on the galactic center.

The conception and search of the black holes started with the ideas of the English reverend Jhon Michell and of the French Pierre Simon Laplace at the end of the XVIII century, and the discovery of the compact object Sirius B by Alvan Clarke in 1862, that was previously conjectured by Friedrich Bessel in 1834. With the fact of finite light speed, the notion of scape velocity, and Newton's law of universal gravitation, supposing that the light was a particles current, it was found that this would not be able to scape of a body that had the same density as the Sun and a ratio 500 times bigger. On the other side, the explanation of the strange nature of Sirius B, today is known as a white dwarf, was possible due to the application of Quantum Mechanics in the Astrophysics. With this, it could be understood that the white dwarfs are the product of a gravitational collapse stopped by the pressure of the electron degeneration. In this form, the Hindu Subrahmanyan Chandrasekhar revolutionized astrophysics when, in 1931, proved the existence of a maximum mass for the white dwarfs. This result generated a big controversy, the existence of more massive stars left the possibility of unsuspected gravitational collapses.

In 1939 Robert Oppenheimer who had worked on the theory of neutron stars, and Harland Snyder using the General Relativity of Einstein, discovered that in some circumstances the gravitational pressure is so large that nothing can stop the contraction of a star by itself. This theory was questioned by the simplicity of its hypothesis. Einstein published an article in Annals of Mathematics, a few months before the Oppenheimer and Snyder publication, where his purpose was to demonstrate the impossibility of black holes.

Roger Penrose in 1965, with the same foundations of the General Relativity, found a strong inevitable consequence of the attractive property of gravitation: although maybe it is not known how to prove that the gravitational sinking of a real star can become in a black hole, it can be proved that it inexorably ends in a singularity, spacetime region where the field equations of Einstein are not valid.

Roger's Penrose work has enriched one of the most beautiful theories of Physics. In a letter written to Einstein at the end of 1915, a month after the appearance of the field equations of the General Relativity, the German astrophysicist Karl Schwarzschild revealed the calculations of an exact solution of these equations, in which he described the gravitational potential of a spherical mass immerse in the physical vacuum, where the gravitation is a manifestation of the curvature of the spacetime, that in essence is Einstein's theory. In 1923 George David Birkhoff demonstrated that the Schwarzschild solution describes not only the geometry of the outer spacetime to a static mass but also is valid around a star in collapse or expansion if it preserves the spherical symmetry. This solution presents two singularities: one of them is associated with the Schwarzschild radius, which is nonessential, it arises from a bad choice of coordinates. This proof took more than 40 years. It was until 1965, thanks to the novel techniques introduced by Penrose, that it was possible to demonstrate that the other singularity, in the core of the system including the solution with Kerr's axial symmetry, could not be eliminated using a change of coordinates. For this reason, the Swedish Academy awarded him with half of the Physics Nobel Prize 2020. The contribution of Roger Penrose to the development of the General Relativity is based on his theorems of singularity, whose demonstrations in that time surprised with the topological techniques and the ingenious manner of working with the concept of a closed surface, trapped in the future, rather than with the notion of the event horizon. While his contemporary partners worked the General Relativity with the concepts of Riemannian geometry and differential geometry, as the metric and the curvature, Roger Penrose introduced the powerful tool of differential topology, with an emphasis on the conformal diagrams of the causal structure of spacetime, the notion of trapped surface and the singularities.

In 1965 Roger Penrose published the article that the Swedish Academy has highlighted as his grand contribution to the theory of black holes: *Gravitational Collapse and Space-Time Singularities* that appeared in Physical Review Letters, volume 14, number 3, January 18 of 1965. The theorem sets out an inconsistency under the supposition of global structure conditions, the local non-negativity of the energy and the future completion of the null geodesics. The argument consists of demonstrating that the existence of a trapped surface implies, independently of the symmetry, that the singularities necessarily exist. None of the theorems leads directly to the existence of singularities. What is done is to prove that spacetime is not geodesically complete and furthermore that it cannot be extended to geodesically complete spacetime. This means that the proof of the 1965 theorem was made by the reduction to the absurd, supposing that all the null geodesics are complete. Then, under plausible physics hypothesis, like the matter that collapse has a density of positive energy, the collapse always ends in the formation of a trapped surface, a region of which not even the light can escape. The notion of the trapped surface is independent of the coordinates and the symmetries. Also, it is surprising that the theorem avoids defining the singularity concept, and as will be seen later, it has complex mathematical implications. The other half of the Nobel Prize recognizes the observational counterpart of the investigation in the black hole physics. The award goes to the systematic work of the research groups, one lead by Genzel and the other one by Ghez, that competing, strengthened their results of more than 25 years of systematic observation of a group of stars gravitating around a supermassive invisible object with a mass of 4 million of solar masses in the center of our galaxy at 26,000 light-years in a region called Sagittarius A*.

At the end of the 1950s, the firsts quasars were found, many of them were registered as radio sources without a correspondent visible object. In the following decades in the sky would appear extraordinary energy sources that encourage the theoretical and observational investigation of collapsed worlds. In 1965 an X-ray source was discovered in the Swan Constellation, afterwards, it was localized and coincide with an optically known star, which is a giant blue, hot and massive, between 25 and 40 solar masses. Since this star cannot emit great amounts of X radiation it was found that the cause is due too that it is a binary system with a compact object that, when it emits gas and is heat up to several millions of degrees is responsible for the source that is known as Cygnus X-1. This compact and invisible partner was one of the first objects considered, with great authenticity, as a black hole.

Recently, a significant advance has been made in the observational research of black holes and super compact objects. With the direct discovery of the first event of gravitational waves on September 14^{th} of 2015 with the LIGO detectors, registered with the name GW150914, indirectly the source of emission was identified as the merger into a black hole of a binary system of black holes with 36 and 29 solar masses, respectively. On April 10^{th}, 2019 it was announced and distributed the image of the proximities of the horizon of an object of 6500 million solar masses in the center of the M87 galaxy, in the Virgin Constellation at 53 million light-years. The image was taken using the observational arrangement Event Horizon Telescope.

In the investigation of compact objects, it has been very important the development of galactic models, where the existence of supermassive black holes in the center of many galaxies is supposed. A technique to determine the mass and properties of these supermassive centers has been the study of the movement of the stars in their gravitational field. But until the last decade of the past century was impossible to use telescopes to observe stars in the center of our galaxy. In this way, Genzel's research group using the 8 meters telescope Very Large Telescope, and Ghez's team working with the 10-meter telescope of the Keck Observatory, started a systematic observation of many stars gravitating around an invisible mass in the Sagittarius A* region, in particular the S2 or So2 star, with the shortest period of 16 years and a very elliptic orbit with an eccentricity of 0,88. The data was registered since 1992 and published since 1994.

The supermassive object in the center of the galaxy is a very bright astronomic source when is observed with radio telescopes, and is not detectable with the visible light due to the interstellar dust. Therefore, it was necessary to observe during many years in the far infrared, k band centered to $2{,}2\mu m$, and also use the telescopes with adaptative optic to correct the perturbative effects on the images due to the turbulence of the atmosphere.

Then considering, among other observations, that the observational evidence shows according to the movement of S2 the existence of a central mass of 4,1 million of solar mass and a radius of less than 17 light-hours in Sagittarius A, it was concluded that none known object that is not a black hole can have these characteristics. However, the investigation of the compact bodies is an open field of research and is in development. Even though the scientific community that which is specialized in this area has understood that this Nobel Prize is the acknowledgment of the theoretical prediction of black holes and to the indirect discovery of one in particular in the center of the Milky Way, there are theoretical models and polemic observations as the GW190814 event that could be alternative explanations of these observations with base in extraordinary compact objects like the generically named *exotic compact objects*.

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