General Relativity and Black Holes

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Gravity or gravitation is the weakest known force among the four fundamental forces in nature which governs the structure and evolution of our universe. A comprehensive view of the universe was initiated with Newton's monumental work. He unified Galileo's theory of falling bodies with Kepler's laws of planetary motion and presented laws of motion and universal gravitation as Newton's theory of gravity.

In Newtonian view, the universe is thought as an infinite three dimensional continuum explained by Euclidean geometry (i.e. three spatial coordinates and absolute time) which describes the flat space.

In 1905, Albert Einstein proposed the special theory of relativity (SR), which changed the face of physics and the way one understands nature and the laws governing it. This theory created a fundamental link between space and time, referred to as the spacetime continuum. SR is based on two well known principles. First is the principle of relativity, which states that the laws of physics are the same in all inertial frames of references. The second one is the principle of the constancy of speed of light i.e. the speed of light is same in all inertial frames of references. Newton's theory didn't fit into Einstein's SR. Now Einstein turned to the development of a new way to understand gravitation. Therefore, after a lot of hard work and repute from famous Michelson-Morley experiment, SR and photoelectric effect, Einstein came up with another remarkable theory, in 1915, known as the **General Theory of Relativity** or **General Relativity (GR)**. GR is a generalisation of the SR, a masterpiece in itself and explains gravity more accurately than the Newton's theory.

This theory has dramatically changed our understanding of space and time (i.e. spacetime) by describing how the curvature of spacetime is related to the distribution of matter (and energy). The famous physicist John A. Wheeler summarised this concept of curvature of spacetime as **"*space tells matter how to move* and the *matter tells spacetime how to curve*"**. The rubber sheet analogy of spacetime is represented in Figure.1.

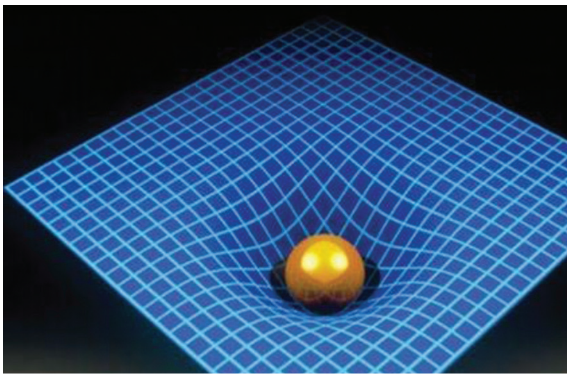

Figure-1: Rubber sheet analogy of spacetime continuum. Here, a massive source curves the spacetime around it.

GR is a physical theory of gravity based on the equivalence principle of gravitation and inertia and on the principle of general covariance. The consequences of GR disclose interesting and fascinating new phenomena like the existence of black holes, the generation of gravitational waves and the fundamental question; how universe is originated?

The language of GR is tensor analysis or differential geometry. Tensors are mathematical object which describe a physical entity. Einstein formulated a fundamental equation that relates the curvature of spacetime with the energy-momentum of matter (radiation), known as ***Einstein's field equation***. In tensor notation, this equation has the form $G_{\alpha\beta}=8\pi T_{\alpha\beta}$.

Here, $G_{\alpha\beta}$ is Einstein tensor and describes the geometry of spacetime and $T_{\alpha\beta}$ is the energy-momentum tensor which represents the mass-energy content, the source of the gravitational field (just as mass is the source of the gravitational field in Newton's scenario).

Black holes (BHs) are one of the most fascinating predictions of GR. BH is a region in spacetime whose gravity is so strong that nothing not even light can escape from inside it. In other words, BH is described as a region where space is falling faster than light. The term BH was coined by John Wheeler in 1967. Mathematically, a BH is an object of zero size and infinite density (but finite mass) called a singularity (It is a mathematical point with virtually zero volume and infinite density).

BH emerges as an exact solution of Einstein's field equations. From a purely theoretical point of view, these solutions have a point-like curvature singularity. This singularity is surrounded by a hypothetical gravitational boundary known as the event horizon, which is one of the unique signatures of a BH. Shortly after Einstein proposed his famous theory of GR, Karl Schwarzschild was the first to obtain a spherically symmetric solution (Schwarzschild, 1916) to the field equations in the theory, known as the Schwarzschild BH (SBH). Since then a number of more generalised BH spacetimes have been obtained in GR like, Reissner-Nordstrom BH, Kerr BH, Kerr-Newmann BH and many others.

The geometrical structure of a BH is depicted in Figure.2.

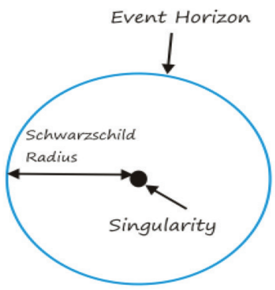

Figure-2: Geometrical structure of a common black hole. Event horizon is the boundary of black hole beyond which we cannot see.

In the life span of a star there is a constant tussle between gravity pulling in and pressure pushing out. The nuclear reactions in the core of the star produce enough energy and pressure to push outward and when a star runs out of nuclear fuel, gravity dominates and the material in the core is compressed even further. The more massive the core of the star is, the more the gravitational pull and thus the star collapses under its own weight. When the nuclear fuel is exhausted and there are no more nuclear reactions to fight against gravity than the smaller stars become white dwarf. Whereas in case of a very massive star, after the exhaustion of nuclear fuel the outer parts of the star are expelled forcibly into space, while the core completely collapses under its own weight and the star explodes as a supernova. Further, if the core remaining after the supernova is still very massive then any repulsive force inside a star cannot hold off hard enough preventing gravity from completely collapsing the core into a BH. Thus, an ordinary type of BH is produced by certain dying stars. For instance, a star with a mass greater than about twenty times the mass of our Sun may produce a BH at the end of its life.

BHs are not just a mathematical concept. They are observable astrophysical objects and their existence is globally accepted by astronomers.

In particular, there are four types of BHs depending on their masses as depicted in Table.1.

Table-1. Types of BHs according to their masses.

	Range of BH mass	**Types of BHs**
1.	Comparable to or less than that of the Earth	Primordial BHs
2.	3 to 20 Times the mass of Sun	Stellar Mass BHs
3.	Equivalent to a few thousand of mass of the Sun	Intermediate Mass BHs
4.	10^6 to 10^9 times the mass of the Sun	Supermassive BHs

These BHs would have formed in different ways. The Primordial BHs are supposed to be formed at the time of the Big Bang, Stellar mass BHs created by the core-collapse of the massive stars at the end of their life. Intermediate ones exist in some highly dense region in galaxies and the supermassive BHs are found at the centres of most large galaxies. Among all these BHs, the stellar mass and supermassive BHs are the most common types of BHs.

A BH itself is invisible because no light can escape from it hence it cannot be viewed directly. The way one can find them is by examining their effects on objects around it. Astronomers have found the evidences and confirmed the locations of BHs by indirect methods like observations of emitted radiation, gas jets, gravitational lens effect and by studying the speed of the clouds of gas orbiting those regions. In the year 2015, astronomers using the Laser Interferometer Gravitational-wave Observatory (LIGO) made the first detection of gravitational waves (one of the consequences of GR) came from merging of stellar BHs. This observation also confirms the existence of BHs in the universe.

The Cygnus X-1 (which is a stellar mass BH) was the first BH detected by the X-ray emissions from the double-star system and is considered a good candidate for a BH. A supermassive BH named Sagittarius A^* exists at the heart of our own Milky Way galaxy and there are several others in various galaxies like, galaxy NGC 4258 and the giant elliptical galaxy M87. Scientists accept that the centre of every galaxy contains a supermassive BH. The current studies also suggest that astronomers have found the most massive BHs ever discovered in our observed universe which are billion times more massive than our Sun.

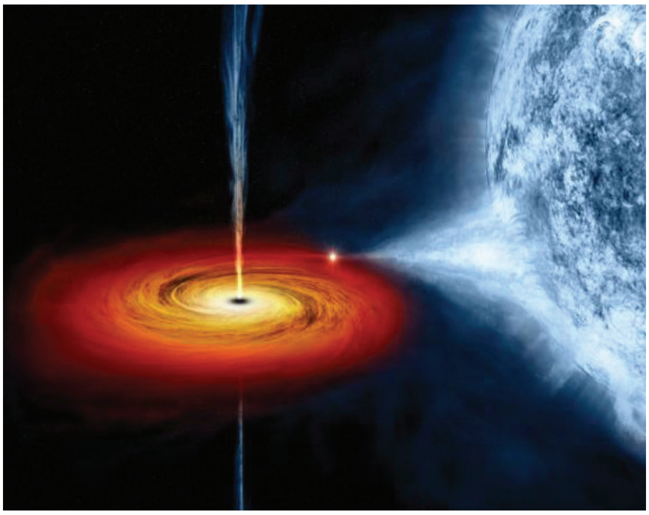

Figure-3: Illustration of Cygnus X-1 black hole. Image credit: NASA/CXC/M. Weiss.

Over the last century, the Einstein's theory of gravitation has proved itself as one of the most successful theories mankind have ever created. BHs are one of the predictions of GR and remain a good recipe for science fiction books, shows and movies.