100 YEARS OF EINSTEIN'S GENERAL THEORY OF RELATIVITY

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About 100 years ago, in November, 2015 Albert Einstein discovered General Theory of Relativity. This revolutionary theory has survived one century of continuous tests of its validity. Einstein's relativity theory has changed our notions of space and time about 100 years ago. The resulting interplay between geometry and physics has dominated all of fundamental physics since then. In this article a general idea of General Theory of Relativity, its tests and importance have been discussed.

Introduction

2015 marked an important milestone in the history of physics. About 100 years ago, in November, 2015 Albert Einstein wrote down the famous field equations of General Relativity, which was presented before the Prussian Academy of Science on November 25, 1915. This work was published in March 1916 in the journal Annalen der Physik. All known gravitational phenomena, such as attraction between two bodies, orbiting planets, etc. can be explained by the General Theory of Relativity (GTR). This revolutionary theory has survived one century of continuous tests of its validity despite numerous expert attempts to find flaws. It marked a major leap from Newton's universal law of gravitation which had been accepted for more than two hundred years as a valid description of the gravitational force between masses. According to the law, gravity is the result of an attractive force between massive objects. This law was extremely successful at describing motion.According to GTR, the observed gravitational effect between masses results from their warping of space-time; space and time are dynamical and influenced by the presence of matter. Several effects, such as minute anomalies in the orbits of Mercury and other planets, which are unexplained by Newton's law, can be explained by GTR. It also predicts novel effects of gravity, such as gravitational waves, gravitational lensing and an effect of gravity on time known as gravitational time dilation. Many of these predictions have been confirmed by experiment or observation, most recently gravitational waves.Einstein's relativity theory has changed our notions of space and time about 100 years ago. The resulting interplay between geometry and physics has dominated all of fundamental physics since then. It provides the foundation for the current understanding of black holes, where the gravitational effect is so strong that even light cannot escape.General relativity is also part of the framework of the standard Big Bang model of cosmology.In this article General Theory of Relativity and its implications will be discussed.

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From Special Theory of Relativity to General Theory

Einstein discovered Special Theory of Relativity in 1905. It is valid for systems that are at rest or at uniform motion, that is where no force acts. According to the theory the laws of Physics are the same for all non-accelerating observers and the speed of light in vacuum is the same irrespective of the speed of the observer. Einstein found that space and time were interwoven into a single continuum known as space-time. Special theory cannot be used generally when there is a gravitational field present. In his General Theory of Relativity Einstein removed the restriction that no force is present so that he could apply his ideas to the gravitational force. As Einstein worked out the equations for GTR he realized that massive objects causes a distortion in space-time.

The Theory

General theory of relativity provides a unified description of gravity as a geometric property of space and time, or space-time. In particular, the curvature of space-time is directly related to the energy and momentum of whatever matter and radiation are present. The relation is specified by the Einstein field equations, a system of partial differential equations. These equations specify how the geometry of space and time is influenced by whatever matter and radiation are present, and form the core of Einstein's GTR. According to Einstein's theory space and time are dynamical and are influenced by the presence of matter. Space-time gets distorted and this is the cause of attraction between bodies. It may be visualized as placing a large body in the centre of a trampoline which will depress the trampoline and a body placed at the edge of the trampoline will move towards the large body as if there is attraction between the bodies. Einstein proposed that an object a would feel a gravitational force proportional to its mass in the presence of another mass, as stated in Newton's law of gravitation. Some predictions of the theory, such as gravitational time dilation, gravitational lensing, gravitational redshift of light, etc., differ significantly from those of classical theory, especially concerning the passage of time, the geometry of space, the motion of bodies in free fall, and the propagation of light.

It correctly accounted for the "anomalous" precession of the perihelion of Mercury and it was able to unify Newton's law of universal gravitation with special relativity. In 1916 Einstien himself proposed three tests of general relativity[1,2]

1. the perihelion precession of Mercury's orbit
2. the deflection of light by the Sun
3. the gravitational redshift of light

The predictions of general relativity have been confirmed in all observations and experiments to date. However, unanswered questions remain, the most fundamental being how general relativity can be reconciled with the laws of quantum physics to produce a complete and self-consistent theory of quantum gravity.

Tests of General Theory of Relativity

Let us now discuss some tests which confirm General theory of relativity.

The Perihelion Precession of Mercury's Orbit : The planets move round the Sun in elliptic orbits. The periapsis of the planets precess round the sun. Newton's laws could correctly predict the amount of precession of the planets other than Mercury. The actual rate of the precession (574.10±0.65 arc seconds per tropical century) disagreed from that predicted from Newton's theory by 38 arc seconds per tropical century (re-estimated at 43 arc seconds)[3]. Einstein showed[2] that General Relativity agrees closely with the observed amount of perihelion shift. The perihelion shift of Earth's orbit due to general relativity is of 3.84 arc seconds per century and that of Venus is 8.62 arc seconds per century. Both values are in good agreement with observations.[4] The periapsis shift of binary pulsar systems have been measured, amounting to 4.2º per year.[5] These observations are also consistent with general relativity.

The Deflection of Light by the Sun : Henry Cavendish and Johann Georg von Soldner pointed out that Newtonian gravity predicts that star light will bend around a massive object[6]. But the amount of bending calculated on the basis of Newtonian gravity was about half the actual bending of light by the Sun. The correct value of light bending was first calculated by Einstein based on his General Theory of relativity. This was experimentally verified by Arthur Eddington and his collaborators in May, 1919 during a total solar eclipse[7] so that the stars near the Sun could be observed. Some expressed doubts about the accuracy of Eddington's measurements, but the observation of a team from the Lick Observatory during the 1922 eclipse, observation by the astronomers of Yerkes Observatory during the 1952 solar eclipse and by a team of the University of Texas during the 1973 eclipse showed that their measurements confirmed Eddington's results[8,9,10].

The Gravitational Redshift of Light : Einstein predicted the gravitational redshift of light based on his GTR that is, the frequency of the electromagnetic radiation emitted by a source in a gravitational field will be reduced, i.e., red shifted when observed in a region of weak gravitational field. The first successful measurement of redshift was made in 1959. In this year Pound- Rebka experiment measured the relative redshift of two sources situated at the top and bottom of Harvard University's Jefferson tower using an extremely sensitive phenomenon called the Mössbauer effect[11] .The result was in excellent agreement with general relativity. This was one of the first precision experiments testing GTR.

The expected amount of redshift for light from the surface of a massive object reaching a distant observer is proportional to the object's mass divided by its radius. Thus White Dwarfs, having masses close to that of the sun, but radii smaller by factors near 100 are interesting candidates for observation: White dwarfs have masses close to that of the sun, but radii smaller by factors near 100. So the red shift of light from white dwarfs should be 100 times more than the light from the Sun. Several efforts were made to measure the gravitational redshift of light reaching us from the white dwarf Sirius B, particularly by Walter S. Adams at Mt. Wilson Observatory[12]. The result agreed with Einstein's prediction. This was one of the first precision experiments testing GTR.

Gravitational Waves : Albert Einstein predicted the existence of gravitational waves and first derived the basic properties of gravitational waves in 1916 in his general theory of relativity. Gravitational waves are 'ripples' in the fabric of space-time caused by some of the most violent and energetic processes in the Universe. There were theoretical debates on gravitational waves, but no one could conclusively detect the waves till September 14, 2015, about 100 years after its prediction by Einstein[13]. The twin Laser Interferometer Gravitational-Wave Observatory (LIGO) detectors, located in Livingston, Louisiana and Hanford, Washington, USA detected a strong gravitational wave signal with a signal-to-noise ratio 24. A careful analysis showed that the observed gravitational wave is from the last 0.2 seconds of the merger of two black holes of masses about 36 and 29 times the mass of the Sun. This confirms a major prediction of Einstein's GTR and opens an unprecedented new window onto the cosmos.

Light Travel Time Delay : GTR predicts a time delay that becomes progressively larger when the photon passes nearer to the Sun due to the time dilation in the potential of the Sun. Observing radar reflections from Mercury and Venus just before and after it is eclipsed by the Sun agrees with general relativity theory at the 5% level[14]. A similar experiment gave agreement with general relativity at the 0.002% level.[15]

Implications of GTR

Einstein's theory has important astrophysical implications. For example, it implies the existence of black holes—regions of space in which space and time are distorted in such a way that nothing, not even light, can escape—as an end-state for massive stars. There is ample evidence that the intense radiation emitted by certain kinds of astronomical objects is due to black holes; for example, microquasars and active galactic nuclei result from the presence of stellar black holes and black holes of a much more massive type, respectively. In addition, general relativity is the basis of current cosmological models of a consistently expanding universe. Astronomers use gravitational lensing (bending of light around a massive object, such as a black hole) to study stars and galaxies behind massive objects.

Conclusion

We have shown that Einstein's general theory of relativity is a major leap from Newton's law of gravitation and has changed our notions of space and time. Not only all known phenomena can be explained by GTR some effects which cannot be explained by Newton's law can also be explained by GTR. Some tests which confirm GTR have been presented. Finally, the implications of GTR have been discussed.It has developed into an essential tool in modern astrophysics. ❐

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