General Relativity In A Bird's Eye View

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Abstract

Over a century, theory of relativity is making its mark as one of the most beautiful physical theories ever existed. Considered as the cornerstone of cosmology, it acknowledges its complexity as its beauty. In this brief yet precise review, we explore the testing foundation, theoretical and mathematical framework as well as the limitation and applications of the theory. We also discuss the recent advances made accompanying the current status of the field, thereby evaluating the potential of the theory in the near future.

Introduction

One of the achievements of the theory of relativity is that it is speculated as one of the most validated and verified theory time and again as it is consistent with the experimental data.The theory of relativity incorporates two interrelated theories in it, namely, Special theory of Relativity and General Theory of Relativity. The theory of relativity is conservative in nature and speculate the origins of gravity. Developed by Einstein in 1905, special theory of relativity unravels new era of physics by introducing a brand new concept of spacetime, thereby, discarding old notion of Newton's absolute space and time. During its initial years, the theory was completely ignored by physicists of that time. In 1920, finally the physics community accepted the theory and start exploring it. Special theory of relativity becomes stepping stone to general theory of relativity. As claimed by Einstein , special theory of relativity was somewhat incomplete, so to complete it, he spent 10 years of his life doing strenuous efforts and finally introduce the concept of 'gravity' to the world, and called it the general theory of relativity. It got published in the late 1915, in it , he determined that the spacetime gets warped around the distribution of mass (massive objects)and energy . Currently ,it is considered as the most accurate scientific theory to predict gravitational interactions. In 1917, assuming the universe to be static, Einstein discovered the field of relativistic cosmology, after applying his theory to universe as a whole. To remain consistent with the observational evidences , Einstein added 'Cosmological Constant' in his original field equations . In 1929, Hubble published a paper which shows that the universe is not at all static but it is expanding. This changed Einstein's " happiest thought" to the biggest " blunder of his life".(For detailed history see ref.[1])

Theory of Relativity

Spacetime is considered as the dynamic entity. The nature of body is independent of the effects of gravity. Special theory of relativity is a special case of general theory of relativity or the modified abstraction of special theory of relativity is general theory of relativity. The main distinguishing feature of these two interrelated theories is the absence of gravity in special theory of relativity. As a result, general theory of relativity is considered more advanced and is widely applicable.

Theoretical Background

Special theory of relativity is based on the principle of equivalence . The theory will fail if the inertial and gravitational masses are not identical or have different values. Many experiments have done to test the validity of this statement but all experiments have validated its existence.

General theory of relativity often known as the mathematical theory of gravity is just a warping phenomena (of spacetime) around a massive body. Its defining feature is the use of Einstein equations that has consistency, symmetry and the simplicity, although it is complex in nature it incorporates the unification and invariance in it. (For more information see ref.[2])

Mathematical Background

The mathematical structure of general theory of relativity is a bunch of tools and techniques employed in the creation of Einstein's theory of relativity giving birth to Einstein's field equations. These tools and techniques are used to define spacetime via tensor fields in a Lorentzian manifold. To define geometry of spacetime, which is curved , tensors are employed. Tensors are the building blocks of Einstein field equations. Crucial features of general theory of relativity are:

1. Invariance of Physical Laws

2. Concept of Curved Manifold
3. The Metric Tensor
4. Energy-Momentum Tensor.

Einstein's Field Equations (EFEs) And Geodesic Equations : The EFEs accompanied by the geodesic equations , shows trajectory of matter through spacetime [3]. These two equations form the foundation of the mathematical creation of general theory of relativity. The EFE being non linear partial differential equations, complicated at its best , are arduous to solve. Though, there are number of approaches and tactics to solve these equations. The EFEs are written in the form:

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu} \tag{1}$$

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi T_{\mu\nu} \tag{2}$$

where $G_{\mu\nu}$ is Einstein tensor given by:

$$G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} \tag{3}$$

The geodesic equation is written as:

$$\frac{d^2x^\mu}{d\tau^2} + \Gamma^\mu_{\alpha\beta}\frac{dx^\alpha}{d\tau}\frac{dx^\beta}{d\tau} = 0 \tag{4}$$

Eq. (1) is the so-called Einstein field equation with its generalized form Eq. (2). The geodesic equation. Eq. (4) , ascertain how the trajectories of objects evolve in a curved spacetime. The parallel transport of a vector in curved space is given by geodesic. Its crucial feature is that it is used for the determination of the paths of particles and radiation in curved space.

Limitation

Despite incredible successes of theory of relativity both in terms of theoretical and experimental verification, the theory is incomplete. One of the shortcoming of this theory is black hole. At the singularity of a black hole this theory breaks down. The questionable nature of cosmological constant [4] and the open question of the unification of quantum mechanics and general theory of relativity poses another shortcoming. Due to these limitations, there are many challenging questions in theoretical physics- Is singularity inevitable attribute of space? Problem of dark sector etc. All these questions are directly related to the inherent features of gravity.

Testing Foundation

Though there are no instrument that can measure spacetime. Warping of spacetime around massive objects confirmed the validity of theory of relativity. For example, recently, a star S2, orbiting the Milky Way's giant black hole (Saggitarius A*) confirms that the light from the star gets distorted as it approaches the giant black hole[5]. This proves Einstein's prediction right. Apart from other experiments and tests [6], to further research in this field community of scientists came up with advanced experiments like MICROSCOPE, STEP, HYPER, APOLLO LLR FACILITY and the LATOR mission which will give an exciting prospect to give insights in the field of general relativity.

Applications: Although the theory seems quite abstruse in nature, but it has really important applications. These applications are direct evidence of the validity of theory of relativity. Some of them are :

Global Positioning System (GPS): Its preciseness depends on rectification from general relativity. Gravity is experienced by GPS satellites above earth. Earth's gravity is four times stronger than that experienced by GPS satellites. General Relativity dictates that clocks travelling in weaker fields ticks rapidly thus helping in navigational errors [7].

Astrophysics : It accurately foretell the rate of growth of galaxy clusters accompanied by a new approach to investigate the universe which is currently accelerating and expanding. Gravitational lensing [8] , gravitational redshift and strong gravity encompassing a black hole are some of the consequences [9] of theory of relativity. It is the groundwork of current cosmological model of universe which is steadily expanding with respect to time . These astrophysical implications have been observed by LIGO collaboration.

Apart from this, the theory also find application (mentioning few)in electromagnets, gold's yellow colour and the fact that mercury is a liquid and gold does not corrode easily .

Advances And Current Status

The LIGO Collaboration provides the direct detection of gravitational waves which is considered as " enormous progress" made in the field of astrophysics in a decade. Some of the ongoing projects include the NANOGraV , Advanced LIGO (US based) and the Parkes Pulsar Timing Array (using pulsars to search for gravitational waves). Hundred years after its debut, theory of relativity emerged as a vital area of research as it is rich with potential for advance investigation. This drastic progress of Einstein's theory from an interesting equation to highly successful model of gravitation and cosmology to a powerful research tool is undoubtedly encouraged by new technologies, powerful computer simulations, increased research funding, stronger partnership between the fields of physics and mathematics which lead to the growth of science community in the understanding of the theory and its real world implications. Currently, it is considered as the best cognizance of gravity and cosmos.

Conclusion

We discuss the various aspects of theory of relativity and evaluated the advances and current status of the field. The recent progress and the upcoming decade of revolutionary discoveries will establish an encompassing theory (which will modify theory of relativity, thus completing it) and definitely will lead to the unification of quantum theory with theory of relativity. This unification will vanish many of the unresolved problems (cosmological constant problem, origin and age of our universe etc) of theoretical physics, thus, ultimately mapping the universe.

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