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Understanding gravity and its effects on the universe

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Abstract

In this chapter, we describe the phenomenon of gravitation. It is the weakest of the four known fundamental forces, and yet it governs the nature of astrophysical objects like stars and galaxies, and the structure and evolution of the whole Universe. Gravity was first recognized as a universal force between any two particles of matter by Isaac Newton in the seventeenth century. Using his famous law of gravitation and the calculus that he independently developed, Newton was able to describe the motion of objects near the surface of the Earth, the orbit of the Moon around the Earth and the orbits of planets around the Sun. In spite of all its successes, Newton's theory is not consistent with the special theory of relativity. That led Albert Einstein to develop an astonishing new theory, known as the general theory of relativity, which describes gravity as the expression of curvature in space- time, produced by matter and energy. Einstein's theory is compatible with special relativity and it agrees with Newton's theory when gravity is weak as in the Solar system. It is able to account for a small discrepancy in the observed orbit of the planet Mercury compared to the orbit predicted by Newton's theory, predict the correct value for the bending of light due to gravity and predict the existence of gravitational waves. The gravitational bending of light is at the basis of the gravitational lensing, which has proved to be an important tool for astronomers.

Introduction

Several issues and shortcomings emerged in the last thirty years leading to the conclusion that Einstein's General Relativity is not the final theory of gravitational interaction. The goal of this Report is to take into account some of these problems to show that more general approaches to gravity have to be pursued.

The Review article is organized in three parts. Each part has an introduction, a main body and is self-contained.

Part I is devoted to a general discussion of gravitational interaction under the standard of gauge theories. Our aim is to show the path that led to General Relativity, its self-consistency and successes in addressing open problem at Einstein's time. A summary of shortcomings emerged later is given. In particular we discuss problems at infra-red and ultra-violet scales. After we review the Gauge Theory showing that General Relativity comes out from local gauge transformations, local Poincaré invariance and space–time symmetries. The role of space–time deformations and conformal transformations is discussed in view of Extended Theories of Gravity. We close this part by pointing out the physical meaning of General Relativity, in particular discussing the Equivalence Principle, the geodesic and metric structures, the post-Newtonian and post-Minkowskian limits.

Part II is the main part of this Report. After a general discussion of Extended Theories of Gravity, we provide a summary of their emergence in Quantum Field Theory formulated in curved space–time. We develop the variational principles and the field equations for some classes of Extended Theories in metric and Palatini formalism. Conformal transformations and their physical interpretation are widely discussed. The role of torsion in these theories is analyzed. Besides, we develop their jet-bundle representation in order to put in evidence the role of symmetries and conserved quantities. After we present the Hamiltonian formulation

showing how it can be connected to the problems of cosmological constant and renormalization at one-loop level. Finally the Initial Value Problem, in various formulations, is addressed showing that the well-formulation and well-position are still not available for any Extended Theory of Gravity.
Part III is devoted to the applications. We consider exact solutions in spherical and axial symmetry. After we develop post-Newtonian and post-Minkowskian limits. The main achievement is the fact that further features as corrections to Newton potential, new polarizations and new gravitational modes emerge with respect to General Relativity. In our opinion, these characteristics will be the test-bed capable of confirming or ruling out Extended Theories of Gravity.
We conclude the Report with some Appendices containing notations, zeta-function regularization and technicalities on Noether symmetries.
It is remarkable that gravity is probably the fundamental interaction which still remains the most enigmatic, even though it is related to phenomena experienced in everyday life and is the one most easily conceived without any sophisticated knowledge. As a matter of fact, the gravitational interaction was the first one to have been put under the microscope of experimental investigation, obviously due to the simplicity of constructing a suitable experimental apparatus.
Galileo Galilei was the first to introduce pendula and inclined planes to the study of terrestrial gravity at the end of the 16th century [1], [2], [3], [4], [5]. Gravity played an important role in the development of Galileo's ideas about the necessity of experiment in the study of Science, which had a great impact on modern scientific thinking. However, it was not until 1665, when Isaac Newton introduced the now renowned "inverse-square gravitational force law", that terrestrial gravity was actually related to celestial gravity in a single theory [6], [7].
Newton's theory made correct predictions for a variety of phenomena at different scales, including both terrestrial experiments and planetary motion.
Obviously, Newton's contribution to gravity, quite apart from his enormous contribution to physics overall, is not restricted to the expression of the inverse square law. Much attention should be paid to the conceptual basis of his gravitational theory, which incorporates two key ideas:

1. The idea of absolute space, i.e. the view of space as a fixed, unaffected structure; a rigid arena where physical phenomena take place.
2. The idea of what was later called the Weak Equivalence Principle which, expressed in the language of Newtonian theory, states that the inertial and the gravitational mass coincide.

Section snippets

A summary of gauge symmetries

Modern gauge theory has emerged as one of the most significant developments of physics of XX century. It has allowed us to realize partially the issue of unifying the fundamental interactions of nature. We now believe that the Electromagnetism, which has been long studied, has been successfully unified with the nuclear weak interaction, the force to which radioactive decay is due. What is the most remarkable about this unification is that these two forces differ in strength by a factor of

Gravity from gauge invariants

The above considerations on gauge symmetry can be developed for gravity. In this section, before discussing the physical meaning of GR, we will derive in a very general way the field equations considering manifolds equipped with curvature and torsion. Specifically, we want to show the role of global and local Poincare invariance and the relevance of conservation laws in any theory of gravity. The approach is completely general and suitable for spinor, vector, bivector and tetrad fields

Deformations and conformal transformations

To complete the above considerations, it is worth noticing that also space–time deformations can be related to the generation of gravitational field. In this section, we develop the space– time deformation formalism considering the main quantities which can be related to gravity. The issue to consider a general way to deform the space–time metrics is not new. It has been posed in different ways and is related to several physical problems ranging from the spontaneous symmetry breaking of

The physical meaning of General Relativity

GR, as we discussed above, is a theory of gravitation that was developed by Albert Einstein between 1907 and 1915. According to GR, the observed gravitational attraction between masses results from their warping of space and time. Up to the beginning of the 20th century, Newton's law of universal gravitation had been accepted for more than two hundred years as a valid description of the gravitational force between masses. In Newton's model, gravity is the result of an attractive force between

Quantum field theory in curved space–time

At small scales and high energies, an hydrodynamic description of matter as a perfect fluid is inadequate: a more accurate description requires quantum field theory formulated on a curved space, in the framework of either GR or another relativistic theory of gravity. Since, at scales comparable to the Compton wavelength of the relevant particles, matter must be quantized, one can employ a semiclassical description of gravitation in which the Einstein equations assume the form

Variational principles and field equations in metric formalism

Having discussed the more general aspects of gravitation theory and briefly reviewed or mentioned some alternatives to GR, we will concentrate now on a number of specific gravitation theories that have received attention lately. We begin by devoting this section to the exploration of their theoretical aspects. In the following, their phenomenological aspects will be studied as well. The theories considered can come from an action as can many of the interesting theories of gravity. We

The Palatini formalism

The fundamental idea of the Palatini formalism is to regard the (usually torsion-free) connection entering the definition of the Ricci tensor as a variable independent of the space–

time metric The Palatini formulation of GR is equivalent to the metric version of this theory as a consequence of the fact that the field equations for the connection give the Levi- Civita connection of the metric [156]. As a consequence, there is no particular reason to impose the Palatini

Conformal transformations and Extended Theories of Gravity

We have already mentioned the Jordan and the Einstein frame on several occasions: it is now time to look in detail at the conformal transformations providing different representations of ETGs and a solution-generating technique. In this subsection we present of conformal transformations application of conformal transformations to Brans–Dicke gravity first, and then to more general scalar-tensor and theories.

Extended Theories with torsion

In this section, we want to face the problem to study gravity considering also torsion. Torsion theories have been taken into account firstly by Cartan and then where introduced by Sciama and Kibble in order to deal with spin in GR (see [127] for a review). Being the spin as fundamental as the mass of the particles, torsion was introduced in order to complete the following scheme: the mass (energy) as the source of curvature and the spin as the source of torsion.

Up to some time ago,

The bundles framework

In some papers [377], [378], [379], a new geometric approach for Gauge Theories and GR, in the tetrad-affine formulation, has been proposed. It is called the bundles framework (from now on the bundles).

The starting point for the construction of such a framework is that several field Lagrangians have corresponding Lagrangian densities which depend on the fields derivatives only through suitable antisymmetric combinations. This is the case of the Einstein–Hilbert Lagrangian which, in the

The Hamiltonian formulation

Here we want to face the problem to study gravity at a fundamental level. In particular, in the framework of the Arnowitt–Deser–Misner (ADM) formalism [36], we want to investigate the possibility to find out cosmological terms as eigenvalues of generalized Hamiltonians in a Sturm–Liouville-like problem.[22] This issue is particularly relevant from several

The initial value problem

Another important problem is the initial value formulation. There are several criteria for the viability of a theory of gravity, and one of them is certainly the property of having a well- posed initial value problem in order to guarantee that the theory has predictive power [156]. The Cauchy problem of theories described by quadratic actions in curvature invariants was studied in [410], [187] and found to be well-posed (in four space–time dimensions, the Gauss–Bonnet identity allows one to drop

Spherical and axial symmetry

In all areas of physics and mathematics it is common to search for insight into a theory by finding exact solutions of its fundamental equations and by studying these solutions in detail. This goal is particularly difficult in non-linear theories and the usual approach consists of assuming particular symmetries and searching for solutions with these symmetries. Stripped of inessential features and simplified in this way, the search for exact solutions becomes easier. In a sense, this approach

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