A REVIEW OF MOVEMENT TO THE GENERAL THEORY OF RELATIVITY AND GRAVITATIONAL WAVES (100 YEARS OF EXPECTATIONS)

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Abstract: The general key ideas leading to the creation of the General theory of relativity and the prediction of gravitational waves are considered in the paper. The material is presented using a historiographical method which allows tracing the origination and further movement of the concepts that became kinematic and dynamic innovations in theoretical physics. The main objective pursued by authors is to develop an algorithm of actions for teachers for familiarizing of interested students of non-physical areas with scientific content of the General theory of relativity, its role in fundamental knowledge system in our days and prospects for experimental detection of gravitational waves for science and civilization.

Keywords: theory of relativity, gravitational waves, Einstein, Gauge Principle, Principle of General Covariance.

1 Introduction

A remarkable event of the year 2017 was the Nobel Prize in physics awarded by American scientists Rainer Weiss, Barry Barish, and Pile Thorn for experimental discovery of gravitational waves. Simultaneous detection of gravitational waves emitted during the merger of two massive black holes by two LIGO detectors was officially announced on February 11, 2016. (1-2) This was after more than a hundred years of waiting since the creation of the General theory of relativity and prediction of gravitational waves. It was a result of about half a century of efforts in trying to detect them (beginning with experiments of John Weber in 1969).

As a consequence of the General theory of relativity (GR), distribution of space-time perturbations in the form of waves was described by A. Einstein (3) in his paper "On Gravitational Waves" published in 1918. All variants of theories of gravity which are based on special relativity predict the existence of gravitational waves. The modern theory of gravity describes events which occur at the confluence of two astrophysical black holes almost in the same way –strong distortion of the space-time requiring enormous energy with subsequent relaxation in the form of fading gravity wave.

From a theoretical point of view, the existence of gravitational waves, at first glance, does not give something new for fundamental physics – mathematical derivation of the wave equation for metric perturbations from the equations of General relativity was performed correctly a long time ago, the process possibility is predicted, the wave parameters are estimated. It seems that analysis of the most complex process occurring in areas of the strong curvature of space and its possible observable consequences promise nothing particularly new for the physics of space-time being one of the bases of a holistic scientific worldview.

However, it seems apparent that the confirmed discovery (existence and main features of gravitational waves were recorded repeatedly since the first observation) shows not only the power of the human mind, efficient interaction of scientists from different countries and growing possibilities of modern technologies, but also absolutely unimaginable in earlier times advance of research of early stage of the Universe by means of new science - gravitational-wave astronomy.

While speaking about physical education in high schools, all the more in secondary schools, we face the challenge in explanation to students of scientific content and general prospects of such grandiose achievements of civilization. On the one hand, such discoveries for which Nobel prizes are awarded may be of interest for students, but, on the other hand, this is opposed to a set of clichés such as "we will not understand this", "what's in it for me", "why should I think about the prospects of all mankind", "that's interesting, but so far away from me." In this situation, it becomes problematic to evaluate the significance of such great discovery. In this paper, authors offer algorithm of the action taking into account that the General theory of relativity is not included, as a rule, into lesson plans in physics in many areas of education at all levels, both in technical and pedagogical universities, etc.

2 Materials and Methods

That is why we have chosen the historical-genetic method of description, namely: how the original idea appeared and became clear, which way did they go in theory and practices, what is the place of theory in fundamental knowledge system now and what are prospects of this discovery for the theory of gravity itself, for science and civilization in general. Surely, when possible, our paper should be focused on a clear presentation of ideas and their consequences, avoiding technical details, detailed descriptions of mathematical equations and procedures.

The purpose of the presented in the paper material is to take a path that led to theoretical proof of the existence of gravitational waves and to their detection without going into details of mathematical subtleties of the theory, but also to explain that high evaluation which was given to this really epoch-making proof of the Einstein gravitation theory.

2.1 Starting point: problems considered in the Special theory of relativity (SR)

We would like to emphasize that the basic idea of SR is a generalization of the Galilean principle of relativity (invariance) for classical mechanics by the inclusion of electromagnetic interactions. Within SR, taking into account all types of interaction, laws of motion have the same form in all inertial frames of reference; the way of these laws writing down in a form which is invariant to reference system is found. Implementation of this postulate and postulate of the speed of light constancy lead to a new kinematics in the framework of space-time forming a unified 4-dimensional manifold.

2.2 Was Albert Einstein satisfied with the degree of SR generality?

For this, it is very important to analyze those driving reasons that lead Einstein to the generalization of the principle of relativity to non-inertial frames of reference. It should be noted that the formulating of the General theory of relativity begins in the paper "On the Relativity Principle and the Conclusions Drawn from It", published in December 1907 in journal "Jahrbuch der Radioaktivität und Elektronik", from section V "Principle of Relativity and Gravitation". Speaking about the possibility of applying the principle of relativity to systems of reference moving relative to each other with acceleration Einstein (4) says that "...this question has to arise before everyone who follows closely implementation of the principle of relativity so far, I cannot but express the opinion on this matter here." The paper shows that the gravitational mass equal to E/c^2 corresponds to the gravitational field energy E. Thus, the law of interdependence, equivalence of energy and mass, is valid not only for the inertial mass, as established by Einstein in 1905, but also for the "gravity" masses (5). The basis for the approach is the idea of the field of gravity interpretation in as a reference system moving uniformly accelerated.

In the book on Einstein scientific activities, A. Pais (6) quotes Einstein's manuscript that has not been published yet and now is stored in Pierpont Morgan library in New York City. In the manuscript, the idea that principle of equality of inertial and gravitational masses can be applied for implementation of the principle of relativity in non-inertial reference system was called "the happiest thought of my (of A. Einstein – authors) life." A. Pais wonders why Einstein thought about the gravity problem? To include gravity in SR or to expand the area of SR application? And he comes to the conclusion that as soon as he wanted to include gravity in the STO, he immediately, or almost immediately, realized that it is possible to expand the scope of his theory (6). So, the Equivalence Principle is a basis of the General theory of relativity: if inertial and gravitational masses are equal, motion in a uniform gravitational field is indistinguishable from motion in a uniformly accelerated system of reference. In other words, no experiment carried out in the laboratory can answer the question whether this laboratory is moving with acceleration or is at rest in the corresponding gravitational field (we will add that this is true in sufficiently small regions of space where the field is uniform, or in the void). Obviously, this is a generalization of Galileo's principle of relativity: no experiment using the laws of mechanics can distinguish one inertial system from another.

3 Results and Discussion

3.1 Critical Analysis of the Equivalence Idea

Let us note some important points:

1. The equivalence principle cannot be included in the theory of relativity because in this case, Global Lorentz Invariance is not valid. On the other hand, maybe it is good to abandon the equivalence principle to which Einstein had remained faithful during the whole time from the moment when this the happiest thought came to him, or it should rise a question about finding a larger group of transformations than the Poincare's group. Namely, the inclusion of an internal "coordinate" system allows formulating the ideas of gauge invariance, generalizing and deepening study of fundamental interaction on the basis of more complete symmetry group;

2. In an inertial frame of reference, in Cartesian coordinates, the 4-dimensional interval $ds^2 = c^2dt^2 - dx^2 - dy^2 - dz^2$

is invariant under Lorentz transformations at the transition from one inertial reference system to another. However, when you transfer to the non-inertial frame of reference, ds^2 cannot be represented as a sum of squares of the four coordinate differentials. Einstein proved this with the example of a uniformly rotating coordinate system. In 1912, in (7) it was stated that, in a uniformly rotating system, due to Lorentz contraction, the ratio of a circumference to diameter should differ from π. The scale is the same as the coordinate axes, which are conventionally presented in the form of rigid rods, although, according to the theory of relativity, absolutely rigid rods cannot exist. Einstein did not doubt that the principle of relativity should remain valid, and raises the question of the necessity of such relativity theory generalization "in order that the theory contains scheduled earlier static gravity fields theory as a special case". Thereby change in the physical concept of world interval is necessary.

In the Special theory of relativity, world lines of free motion are defined as geodesic lines in Minkowski geometry. From the point of view of variance approach, movement along the geodesic lines corresponds to an extremum of the path between two points. In inertial reference systems, the shortest distance between two points is a familiar straight line. In non-inertial reference systems, the geodesic lines have non-zero curvature, and world interval should be expressed not only by coordinates difference (given above differentials represent, in fact, infinitely small differences between the coordinates) but the introduction of quantities describing at each point the curvature of space-time is required. Thus, square of the world interval in a non-inertial frame of reference has the form:

$$ds^2 = g_{ik}dx^i dx^k,$$

where g_{ik} is a function of spatial coordinates x^1, x^2, x^3 and time coordinate x^4. A four-dimensional coordinate system in non-inertial reference systems is curved, and value g_{ik} determines the space-time metric, representing a single object – 2nd rank symmetric metric tensor. For an arbitrary selection of coordinates, a number of different space-time functions is 10; 4 of them have the same indexes, 6 - different indexes. When taking into account symmetry $g_{ik} = g_{ki}$

Physical phenomena should be described by the equations which are invariant under all space-time coordinate systems – this is a principle called by Einstein the General Covariance Principle. The general covariance requirement led Einstein to use of tensor calculus because the equations are explicitly covariant with this language. In the paper written in 1913 together with M. Grossmann (8), in the second, mathematical, part written by M. Grossman is said, "Given the results by Christoffel, Ricci and Levi-Civita developed own method of absolute, i.e. independent of the coordinate system, differential calculus, which allows giving invariant form to differential equations of mathematical physics". Further, in the paper, systematic description of developed by the authors tensor analysis is given. Thus, they are tensor equations which do not distinguish coordinate systems.

The main author objective is to derive the equations, constructed in such a way that invariance of the interval was followed by the covariance of the corresponding system of equations. In the above paper, the equations of gravity are not yet derived, but Riemann curvature tensor g_{ik} appears and the relationship between the gravitational field and tensor determining the interval between world points, i.e., a space-time metric, is clearly formulated.

Einstein, together with Grossman (8), comes to a wrong conclusion that the gravitational field equations can be covariant only with respect to linear transformations. Only in the paper, after a long search, he finally retracted this position (9). Finally, Einstein comes to two ideas – on the gravitational field nonlinearity and local implementation of the principle of equivalence. That is, Lorentz invariance is no longer a global property but plays a central role as a local invariance. The local Lorentz invariance requirement is defined by the difference of field equivalent to non-inertial reference systems from "true" gravitational fields. First, this difference appears in relation to their properties at infinity. "True" gravitational field tends to zero at infinity; the field that is equivalent to the acceleration of the moving system increases unlimited or remains finite at infinity. (10) Second, the true gravitational field cannot be excluded by selection of reference system, while the fields which are equivalent to non-inertial reference systems disappear at the transition to an inertial frame of reference. Thus, the "true" gravitational field can be compensated only in the infinitesimal neighborhood of one point. In this regard, a variety of reference systems are introduced in GR as, in the case of a variable gravitational field, the space metric is not only non-Euclidean but also non-stationary, i.e. depends on the time.

In the General theory of relativity, compared with the Special theory of relativity, the meaning of the reference system concept differs. In the presence of the variable gravitational field, the reference system is a set of an infinite number of bodies, uniformly filling entire space together with arbitrarily running clocks associated with each body (10). Transformations of a curved Riemannian space to itself are transformations from one class of frame of reference to another class. Selection of the class is defined by some additional gauge conditions imposed on the space-time metric.

A. Pais (6) notes that, in GR, new kinematics is closely intertwined with new dynamics. He considers the fact that "Lorentz invariance is deprived of its global validity but continues to play a central role as a local invariance." Dynamic innovation is the gauge principle, the importance of which was not immediately properly understood. Nowadays, it is now known that all physical interactions can be described through local gauge invariance being the conceptual basis of modern physics of high energies and generalizing Einstein covariance principle.

If equations for a physical system in Minkowski space are known, to obtain these equations in an arbitrary reference system in the presence of gravitational field procedure for replacement of tensor differentials with covariant differentials and replacement of partial derivatives with covariant ones should be applied. The procedure for such replacement is described in the paper. (10) It is important to emphasize that the rule of covariant differentiation consists is adding of an additional term. In GR, Christoffel symbols which express a change of vector components in a parallel translation play the role of additional components. Thereby free scaling at the transition from one space point to another that means the trajectory curvature is possible. Requirement for physical law invariance in covariant notation relative to local transformations requires introduction of a gravitational field which have to compensate the effects caused by gauging at transition from point to point (by change in scale – let us note that the term "gauging" is entered into the physics from railway terminology and has a sense of change of the reference level or scale, though now it has a different meaning). The fact is that the gravitational field is not postulated here but is derived as a result of invariance under a group of local transformations, and means a gauge approach to the description of the interaction. This is GR where a representation of the gauge principle, according to which a requirement of invariance of Lagrange function containing all information about the system, introduces for consideration new gauge fields (for example – connectivity, in other words, the Christoffel symbols). Without taking into account interaction with these fields (and their self-acting), the theory is locally invariant.

Gravity is no longer considered as just a force interaction of bodies and fields, the gravitational field cannot be reduced to the scalar gravitational potential of Newton's theory, but it constitutes a specific form of the contained matter - deformation, curvature of space-time and metric of this space-time is a dynamic characteristic of space-time. The gravitational field is a metric field defined as a second rank symmetric tensor field on a smooth manifold in a 4 dimensional metric space, in space-time. Metric defines all of the characteristics of the gravitational field, for example, the gravitational field intensity – connectedness of space-time. The deepest sense is laid in the term "metric tensor": it is this subject which was used by Einstein to describe gravity not only as a physical field similar to the electromagnetic field, but also as an occurrence of changing metric of space-time defined by g_{ik} components.

Thus, implementation of the equivalence principle can be a sequence of mathematically expressed steps: local Lorentz invariance → gauge principle → general covariance.

3.2. The equations of the General theory of relativity.

B. Hoffman notes: "it is impossible to tell <...> about all the difficulties that Einstein had to overcome. Two years (1914 – authors) he was going in the wrong direction, before he figured out (among other things) that from a physical point of view, there is no argument against equivalence of all coordinate systems and, ultimately, the principle of general covariance does not contradict the causality principle". (11) The purpose of the next step was to find ten gravitational equations.

Covariance of the global interval $ds^2 = g_{ik}dx^i dx^k$ required searching of a new geometry and it was the Riemann geometry. Einstein says: " Auxiliary mathematical apparatus necessary for the General theory of relativity already existed in the form of the "absolute differential calculus", whose foundation was laid in the researches of Gauss, Riemann and Christoffel dedicated to non-Euclidean spaces; this calculus, brought in the system by Ricci and Levi-Civitas, have already been used for solving problems of theoretical physics". (12) It is known that Gauss discovered a method which allowed extracting from two-dimensional metric tensor the information about the internal space curvature described by this tensor. The Riemann tensor (Riemann-Christoffel), also called a curvature tensor, appears in the application of Gauss method for the multidimensional case. Einstein could derive the Riemann tensor solely from the metric tensor. This resulted in a deepening understanding of the space-time in which the four-dimensional pseudo-Euclidean space is curved. The most complete information about the curvature is contained, as already mentioned, in the Riemann tensor R^l_{imk} , from which Ricci tensor $R_{ik} = R^l_{ilk}$ and scalar curvature $R = g^{ik}R_{ik}$ can be derived by convolution. Convolution and the operation of the raising and lowering of indices are made by covariant g_{ik} and contravariant g^{ik} components of the metric tensor. Covariant components define an invariant interval of space-time.

The principle of covariance implies that all physical quantities appearing in the laws of physics are representation of a group of diffeomorphisms (a group of arbitrary transformations of 4–coordinates in a Riemannian space-time), and all the members in the ratio having a status of physical laws or being a consequence of them, have the same tensor dimension.

Einstein is an author to the postulate that the tensor of energy-momentum is a source of the gravitational field. The energy-momentum tensor is a second rank tensor; it combines all parameters that determine the acceleration of moving medium in mechanics of the Special theory of relativity - internal forces caused by the environment and its inert properties. Einstein energy-momentum tensor is considered as a physical factor due to which the components of the Riemann tensor become non-zero and this is interpreted as a description of the space-time curvature. In other words, geometric characteristics of space-time in the neighborhood of each point defined by some functional of the curvature tensor $G_{ik}\{R_{lmns}\}$ are related to the amount of located here gravitating matter defined by energy-momentum tensor $T_{ik.}$. The G_{ik} tensor is called Einstein tensor.

It is important to mention that the Riemann tensor - a fourth rank tensor - has 20 independent components, and the energy-momentum tensor has ten components. At that, the Riemann tensor can be expressed in the form of two parts, one of which may be connected with the energy-momentum tensor, and the other cannot be connected. G_{ik} are components of a second rank tensor equivalent to that part of the Riemann tensor, which can be included in the gravity equation with the tensor of energy-momentum. Without loss of generality, it can be agreed that the G_{ik} functional has the same unit of measurement as the curvature tensor - inverse square of length. The unit of measurement of the energy-momentum tensor, as a rule, is selected as the density of energy.

British mathematician Clifford suggested that space should have its own elasticity. It is possible to say that the General theory of relativity is an evolution of this idea. The ratio between geometrical characteristics of space-time and pulse–energy characteristics of matter are written in the form of the law of space-time elasticity: $G_{ik} = -\chi T_{ik.}$ χ constant included in this ratio is interpreted as the coefficient of elasticity of space-time. The idea of elasticity of Riemannian spaces was later developed by A.D. Sakharov (13) who considered gravity as the metric elasticity opposing the curving of space-time.

So, the measure of the curvature of 4-dimensional space-time manifold is the gravitational field. Sources of curvature, that is, sources of the gravitational field, are non-gravitational physical field describing the diversity of elementary particles (in the physics, are conditionally united by the term "matter"). Local characteristics of the "matter" are the energy-momentum tensor T_{ik}. These are Einstein equations which establish a relationship between the space-time curvature in the neighborhood of a point and "matter" in the neighborhood of the same point. (10)

The following principle formulated by Einstein can be called the Principle of conservatism. The meaning of the principle is that T_{ik} cannot be arbitrary, any motion has to comply with the laws of conservation of energy and momentum. Pais notes that, for a certain period of time, conservation laws were a weak point in Einstein theory, is just a limitation of the theory, and not an automatic consequence of general covariance. Initially, Einstein tried to derive the conservation laws without using the variational principle, although in earlier papers he used just the variational principle when trying to find the correct gravitational field equations. (6) Variational principle appears again, but conservation laws still are not a consequence of invariance. (12) Generally, covariant conservation laws of momentum and energy were derived from gravitational field equations together with the postulate of general covariance without using the field equations for the matter. (14) Here we should also mention the Herculean efforts of Einstein followers Weyl, F. Klein, D. Hilbert, Pauli, T. Levi-Civita, Lorentz, E. Schroedinger, and others in giving the General theory of relativity consistency and clarity in these complex issues.

According to Einstein, the conservativeness condition for the tensor of energy– the momentum of matter $T^k_{i;k}$ = 0 has to be an identical relation in the equations of matter motion compatible with the equations of the gravitational field. Thus, the principle of conservatism for a tensor of energy-momentum of matter can be regarded as a generalization of local formulations of the conservation laws of energy and momentum for the case of curved space. Combining this principle with the law of elasticity of space-time, it can be concluded that the functional $G^k_{i;k}$ should also meet the condition of conservatism identically: $G^k_{i;k} = 0$, and this identity must be a consequence of the definition of geometrical quantities.

Another principle adopted by Einstein could be called the criterion of simplicity, according to the principle, the simplest equations of the gravity theory have to be a second order differential equation for the metric tensor g_{ik}. B. Hoffman notes, "Einstein's skill appears in the fact that he gave a description of the theory of gravity with only ten g_{ik} values". (11) The functional G_{ik} which is linear with respect to the curvature tensor meets this criterion.

Particular attention should be paid to the phenomena of gravitation which are described by another part of the Riemann tensor - Weyl tensor. The effects defined by Einstein tensor vanish outside bodies where the energy-momentum tensor is equal to zero, but the gravity effects existing outside the bodies are defined by Weyl tensor. In other words, Weyl tensor describes just the "true" gravitational field. There is a well-known procedure in General theory of relativity by which, after defining of the metric tensor, full Riemann tensor, and Einstein tensor too, and Weyl tensor can be calculated.

The principle of conservatism allows obtaining of G_{ik} functional in the form of Einstein tensor with $\Lambda -$ term, was first introduced by Einstein in 1917 with the aim to derive a static solution of the cosmology equations (15):

$$G_{ik} = R_{ik} - g_{ik}\frac{R}{2} - g_{ik}\Lambda_{grav}, \quad \Lambda_{grav} = const. \quad (1)$$

From a phenomenological point of view, the term containing the Λ_{grav} constant has the status of a conservative member of zero order relative to curvature in the left (geometric) part of the equations of gravitation theory. The other two terms have the status of a conservative member of first order relative to curvature. Conservative terms containing higher derivatives of the metric and the higher degrees of curvature can be formally included into functional G_{ik}. However, such complicated formulas do not satisfy the criterion of simplicity.

The current understanding of the constant physical meaning will be analyzed in connection with the concept of vacuum, especially due to the fact that there are good reasons for identifying of so-called Dark Energy, a medium with negative pressure, with a cosmological vacuum.

It is clear that the scope of this paper does not allow for a detailed discussion of certain topics which can demonstrate "what the General theory of relativity became now." We deliberately left outside the scope of paper a review of the experimental verification of the theory. A lot of publications analyzing details of the origins, formation and current status of the General theory of relativity are devoted to this issue. However, it should be noted that the discrepancy of classical, Newtonian, theory and experiment in determining the perihelion shift of mercury (the axis of Mercury's orbit rotates so that perihelion shifts for 100 years, the calculated angular velocity is 526.7’’, the observed shift is 565’’) was always the center of Einstein attention despite the fact that the main purpose of his arduous search was formulation of correct equations of General theory of relativity. This issue seemed to him important because the correct theory of gravity was required to explain the discrepancy between measurements and theory. This explanation was obtained by Einstein in direct calculations using GR.

3.3 Vacuum and Gravitational Waves: Some Fragments of the Subject "What is the General Theory of Relativity now"

Let us take a look at the Einstein equations in the form of the law of space-time elasticity.

$$R^k_i - \frac{1}{2}\delta^k_i R - \delta^k_i \Lambda_{grav} = \chi T^k_i, \quad (2)$$

where - χ - coefficient of elasticity, equal to $\frac{8\pi G}{c^4}$ and called the Einstein gravitation constant, G is the Newton gravitation constant, c – the speed of light. Two fundamental constants appear in Einstein's theory: constant characterizing the space-time itself, and χ constant characterizing intensity of relationships between matter and geometry.

Ya.B. Zeldovich (16) raised the question: do Einstein's equations permit the existence of Minkowski empty flat space-time? Riemann tensor has to be equal to zero in flat space-time, and, accordingly, all of the Riemann tensor convolutions: $R_{ik} = R^l_{ilk}$ = 0 and $R = g^{ik}R_{ik}$ = 0. The problem of correct definition of empty space is less trivial. Of course, in empty space, there are no particles and waves that move to macroscopic distances. It seems that in this case (when there is void) tensor of energy–momentum of matter should be simply put equal to zero everywhere: T_{ik} = 0 in all space-time. However, this definition of empty space, or in equivalent terminology - vacuum, is not the most general. And this is due to the General theory of relativity, namely, due to the necessity of multiple observers. "Matter" is necessary for the physical realization of the observations program, i.e. the necessity of observer who is exploring this matter together with its inherent geometry, the geometry is defined by the spatial-temporal distribution of matter itself, taking into account its dynamic characteristics. In other words, the existence of "matter" with some dynamics and structure means, as already mentioned, that various reference systems can be implemented at the relevant material bodies equipped with different systems of spatial coordinates and different ways of time measuring.

The motion of matter is represented differently in different reference systems, and this appears in the dependence of the numerical values of components of energy-momentum tensor of "matter" on the selection of the 4-coordinate system. Ya.B. Zeldovich drew attention to the following circumstance: it is necessary for the relativistic theory that the energy density (vacuum) is the same for any observer, i.e. in the most general case, the vacuum should be determined not as the environment with zero tensor energy-momentum $T^{k}_{i(vac)}=0$, but as a relativistic invariant environment with the tensor of energy-momentum not changing when the reference system is changed: $T^{k'}_{i(vac)}=T^{k}_{i(vac)}$. That is, it is impossible to relate any system of reference without matter with a relativistic invariant environment. The only possible tensor that satisfies this definition has the form $T^{k}_{i(vac)}=\delta^{k}_{i}\varepsilon_{vac}, \varepsilon_{vac}=const$ where ε_{vac} is the energy density of the vacuum. Requirement $\varepsilon_{vac}=const$ leads to the situation that the pressure (tension) P is the same for all directions and equal to $P=-\varepsilon_{vac}$. It is important to note that ε_{vac} can be both positive and negative, while ordinary matter and ordinary fields, considered as excitations of vacuum, always make only a positive contribution. So, the physical meaning ε_{vac} is the density of vacuum energy of non-gravitational physical fields. Modern experimental data prove the existence of two vacuum subsystems - quark-gluon condensate (QGC) and Higgs condensate (HC). It was found that $\varepsilon_{vac}<0$ for data of vacuum subsystems.

The Einstein equations for empty space–time with the substitution of T_i^k by T_{ivac}^k and transfer of $\delta^k_i\Lambda_{grav}$ into the right part of the equation, with the substitution of Λ_{grav} by $\chi\varepsilon_{grav}$, has the form:

$$R^k_i-\frac{1}{2}\delta^k_i R=\chi\delta^k_i(\varepsilon_{grav}+\varepsilon_{vac}). \quad (3)$$

Two important conclusions follow from the equations (2). First, the geometric constant Λ_{grav} after trivial changing of notation (in fact, after selecting the system of units) can be interpreted as the energy density of the gravitational vacuum. This interpretation is not surprising. This is because, as noted above, each fundamental interaction has its own vacuum subsystem in existing and experimentally confirmed theory of elementary particles: Higgs condensate with energy density $\varepsilon_{eW}\approx-(246\ \text{GeV})^4$ corresponds to electromagnetic and weak interactions, united in the Salam–Weinberg theory in electroweak interaction; quark-gluon condensate with energy density $\varepsilon_{QCD}=-(265\ \text{MeV})^4$ corresponds to strong (chromodynamic) quarks interaction. And this is despite the fact that the observed vacuum energy density in the Universe is only $+(0.002\ \text{eV})^4$!

It is natural to assume that some particular vacuum subsystem corresponds to the gravitational interaction; the nature and microstructure of this system are currently unknown. The existence of gravitational vacuum subsystems is represented on the phenomenological level in the geometric part of the Einstein equations with a null member of conservative expansion of the tensor by curvature orders.

The second conclusion may be considered as an attempt to answer this question. The Einstein gravity theory permits the existence of empty flat Minkowski space under the condition that the gravitational vacuum energy completely balances the energy of vacuum non-gravitational physical fields:

$$\Lambda=(\varepsilon_{grav}+\varepsilon_{vac})=0. \quad (4)$$

The summary constant is naturally interpreted as the energy density of a balanced vacuum in 4–dimensional space-time.

If Einstein's equations are written for the case when the total density of vacuum energy is equal to zero and there are no particles and waves of non-gravitational nature, it can be found that empty space-time can curve itself. Einstein's equation for "void" $R^k_i-\frac{1}{2}\delta^k_i R=0$ permits solutions which not only describe Minkowski space with Riemann tensor $R^l_{imk}=0$ but a curved space-time for which the equality to zero of the Ricci tensor ($R_{ik}=0$) take place at non-zero Riemann tensor ($R^l_{imk}\neq 0$) included the Weyl tensor. The solution with $R^l_{imk}\neq 0$ is obtained in the case when the metric tensor defining the Minkowski space is represented in the form of "background field + small perturbation", $g_{ik}=g^{(0)}_{ik}+h_{ik}$. Using a formula of Riemann geometry, the Einstein equations for "void" can be obtained and, after averaging of these equations - equations for the background gravitational field. By subtracting from the exact equations the averaged ones, the equation for the gravitational wave, i.e. normal wave equation for perturbations of h_{ik} metric, can be obtained. So, the theory says that gravitational field propagates in vacuum with the speed of light, and this is interpreted as a gravitational wave. Thus, gravity waves propagating in space-time curve the space-time itself. In the course of more detailed analysis, it was found that gravity waves are radiated by only a couple of interacting massive objects (so-called quadrupole radiation), the gravitational waves amplitude - dimensionless relative change in the distance between the points of space-time - is directly proportional to the first derivative of acceleration and mass of the radiating system. Detection of waves with very small amplitude is possible only in the case of large masses and large changes of acceleration.

3.4 Gravitational Waves: A New Tool of Knowledge

Indirect evidence for the existence of gravitational waves was obtained long enough - approaching of close binary stars' systems was accompanied by a loss of energy, which was interpreted as the emission of gravitational waves (Nobel prize in physics for the study of the pulsar PSR 1913+16, R. A. Hulse, J. G. Taylor, 1993).

Meanwhile, due to the already mentioned smallness of amplitude, direct detection of gravitational waves was delayed for quite a long time since their theoretical prediction; massive radiation sources were necessary. Two main kinds of recordable gravitational waves sources are considered in modern astrophysics: 1) collapse of dual black holes; 2) merger of black holes or black hole and a neutron star. Accordingly, experimental strategies have been implemented over the past decade to improve resonant detectors of gravitational waves that went the way from the first John Weber resonance detector to detectors operating in many countries - in Russia (Moscow State University, SAI), Switzerland (CERN), Japan, Netherlands, etc.

The main contribution to their creation was made by Russian scientists B. B. Braginsky, V. I. Panov, A. M. Cherepashchuk, V. N. Rudenko, etc. (17)

However, the second experimental strategy was more successful, it was the creation of laser interferometers which started with the work of the Russian physicists M. E. Gertsenshtein and V. I. Pustovoit (18) "On the Detection of Low-Frequency Gravitational Waves. It was shown in the paper that the sensitivity of the electromechanical experiments for gravitational waves detection using resonant detectors is 10 orders less than predictions of Weber, and a new strategy for their detection was proposed. Thanks to the improvement of technology, use of new materials, growth of computer software capabilities, improvement of the equipment sensitivity, LIGO Observatory implementing laser interferometers was established on the initiative of American scientists K. Thorne, R. Weiss, R. and Dreaver, and based on the ideas of M. E. Gertsenshtein and V. I. Pustovoit (18). The project was developed, implemented and tested beginning from 1993, although the whole ideology of new tool for nature learning was theoretically proved much earlier. (19) The first successful detection of gravitational waves was performed in LIGO Observatory on 14 September 2015 by two gravitational-wave antennas: first, by L1 (Livingston), then by H1 (Hanford), the distance between these antennas was approximately 3,000 km. (19) This was a signal from the merger of two massive black holes (with masses of 29 and 36 solar masses) obtained during the test run of the instrument (!); it is the presence of the two observatories made it possible to capture and compare parameters of moving through the Universe space-time of outburst generated in a massive distortion of space-time at a distance of about 1.3 billion light-years from Earth.

Currently, laser interferometers are applied not only in the USA but also in Italy (VIRGO), Germany (GEO 600), Japan (underground detector KAGRA); measurements at the gravitational-wave antenna LIGO-India will begin in a few years. Detector system under development will be effective not only for detecting of gravitational waves but also for successful triangulation: defining of radiating sources location in the Universe. It should be added that capabilities of space observatories in the search for long-wavelength gravitational perturbations (eLISA project) are already actively tested. Then it will become possible to study supermassive black holes that are expected to be located in the centers of galaxies.

4 Conclusion

Why the discovery of gravitational waves is so important for the development of modern physics? One of the most important problems of modern science is the question of what is the carrier of Dark Energy. According to cosmology observation, Dark Energy makes 73-76% of the energy balance of the Universe unlike elementary particles (4%) and Dark Matter (20-23%). Dark Energy is not structured and it fills the Universe homogeneously and isotropic. If a carrier of Dark Energy in the modern Universe is the balanced vacuum (20), then there is a hope that the observational cosmology data will rather accurately define a value which are fundamental constants of physics. Study of gravitational waves has tremendous potential for solving this problem.

Gravitational waves are the one agent that is able to penetrate into any powerful cataclysm (merging of black holes or neutron stars, supernova collapse, and explosion) in the Universe and to tell what is a mechanism of such process that causes a noticeable space-time deformation. It is only necessary to "catch" and properly "interrogate" the caught, deriving all important information. With the increased sensitivity of detectors, it may be also possible to capture signals generated by massive objects before the actual merge.

It is possible that deviation from Einstein's theory would be detected by analyzing of various known variants of the gravity theory in terms of propagation and characteristics of gravitational waves, for example, in strong gravitational fields. There is hope that the study of gravitational waves will allow us to look into the processes occurred before the Big Bang and processes which lead to this explosion, in particular, to add arguments "for" and "against" in the development of the inflationary Universe model (21), superstring theory (22), to answer the question on the vacuum as the source of abstraction of our world (23-24) and much more else.

The 21st century started with a few great discoveries in physics – the discovery of the Higgs boson, oscillations of massive neutrinos, gravitational waves. In addition, no doubt that many discoveries which have tremendous importance not only for fundamental science but for the whole of human civilization, for each person of the Earth are ahead of physicists.

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