Chapter

The Early Universe as a Source of Gravitational Waves

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Abstract

In this chapter we consider the issues of the origin and evolution of relic gravitational waves (GW), which appear as a result of quantum fluctuations of the scalar field and the corresponding perturbations of the space-time metric at the early inflationary stage of the evolution of the universe. The main provisions of the inflationary paradigm and the methods of the construction of current cosmological models on its basis are considered. The influence of relic gravitational waves on the anisotropy and polarization of the relic radiation and the importance of estimating such an effect on the verification of cosmological models are discussed as well.

Keywords: universe, inflation, scalar field, cosmological perturbations, gravitational waves

1. Introduction

The general relativity (GR) theory proposed by A. Einstein more than a 100 years ago currently finds new confirmations. The possible existence of gravitational waves was predicted by A. Einstein on the basis of solving the equations of general relativity when calculating the power of gravitational radiation [1, 2].

Gravitational waves (GW) are space-time curvature disturbances, which propagate at the speed of light. They occur at any movements of material bodies, leading to inhomogeneous gravity force variation in the environment. Gravitational radiation was predicted by A. Einstein in the general relativity (GR) theory, but so far not detected by direct measurements.

According to general relativity, space-time is curved around the bodies due to the action of gravity and is represented by a symmetric tensor $g_{\mu\nu}$ with 10 independent components. However, far from the masses (the case of weak gravitational fields), the tensor can be divided into two terms $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$ where the first term, i.e., tensor $\eta_{\mu\nu}$, corresponds to the flat space-time of the special theory of relativity and has only four components. The second tensor $h_{\mu\nu}$ contains information about the curvature caused by the gravitational field and makes small corrections. In the case of gravitational disturbances propagating far from their sources, the components of the tensor $h_{\mu\nu}$ can be calculated by the method proposed by Einstein [1], similar to that used in electrodynamics for delayed potentials.

The first evidence was received by experimental studies of Joseph H. Taylor and Joel M. Weisberg et al., who studied the effect of slowing down the period of the binary star system PSR 1913 + 16 due to energy losses on gravitational radiation [3].

Until recently, however, there has remained the main task: the direct recording of gravitational waves from space radiation sources by means of ground-based or space gravitational antennas.

Over the years, several methods have been proposed for recording gravitational radiation. Experimental work began in the 1960s of the twentieth century, but before the beginning of the twenty-first century, there was no reliable experimental proof of the ground-based recording of gravitational radiation [4].

This is due to the fact that gravitational waves have small amplitude; in addition, the proposed detection methods have insufficient sensitivity and are rather complicated in technical implementation.

These are broadband gravitational antennas, which offer a lot of opportunities as to the methods of recording gravitational waves and extracting signals, as well as the use of quantum non-perturbative measurements and the inclusion of gravitational antennas in the network.

The creation of new-generation gravitational antennas designed to reliably receive gravitational waves from remote space sources involves the use of high-power lasers, complex computer systems for processing large data arrays, the use of complex seismic protection systems, and the solution of other complex engineering and physical problems.

At present large international experience has been gained in the field of creating laser gravitational antennas, which ensured the ground-based recording of gravitational waves from black hole collision [5, 6] and neutron star merger [7]. Furthermore, the gravitational wave propagation velocity was estimated, which appeared to be equal to the speed of light in vacuum with an accuracy of 10^{-15} based on almost simultaneous recording of gravitational waves and a short gamma-ray burst from neutron star merger [8].

The modern theory of the early universe is based on the inclusion of the inflationary stage which precedes the stage of the hot universe. The theory of cosmological inflation [9] explains the origin of a large-scale structure and corresponds to observational data [10]. Inflationary expansion of the universe during very early times, once the universe emerged from the quantum gravity (Planck) era, has been proposed in the late 1970s and mainly in the beginning of the 1980s and is becoming more accepted as a necessary stage which modifies the standard Big Bang theory model. According to the theory of inflation, the primordial perturbations appear from quantum fluctuations. These fluctuations had essential amplitudes in scales of Planck length, and during inflation they generate the primordial perturbations which then lead nearer to scales of galaxies with almost the same amplitudes [11].

Thus, the theory of cosmological inflation connects large-scale structure of the universe with microscopic scales. The resultant range of inhomogeneities practically doesn't depend on scenarios of inflation and has a universal form. It leads to unambiguous predictions for a range of anisotropy of the background radiation.

The small quantum perturbations of the scalar field and the corresponding perturbations of the metric generate the relic gravitational waves. This type of gravitational waves was not directly observed; however, the possibility of such observations plays a key role to understand the physical processes in the early universe.

2. Inflationary stage of the early universe

The models of inflationary (accelerated) expansion of the universe at the early stage of its evolution, that is, at times close to the Planck time, are becoming increasingly convincing as a necessary step modifying the standard Big Bang theory, which is based on solutions of Einstein's equations for the universe filled with ordinary baryonic matter with a positive energy density obtained by Friedmann. However, the extrapolation of Friedmann solutions to early times leads to many insoluble problems when constructing on their basis the evolution scenarios of the universe [9].

The exponential (de Sitter) expansion, suggesting $p = -\rho$, or a close expansion of the early universe based on the evolution of a certain substance with the equation of state $p \approx -\rho$, i.e., with a negative pressure, is a feature of inflation models which allow to solve the problems of the standard model of the Big Bang theory, namely, the problems of the horizon, flatness, homogeneity, isotropy, low concentration of exotic states of matter (domain walls, monopoles, etc.), anisotropy of the background radiation, the initial singularity, and some other problems [9].

Thus, the cosmological models containing a combination of Friedmann solutions and (quasi) de Sitter solutions provide the basis for a current description of the evolution of the universe. In the context of the inflationary paradigm, the early universe expands for some time accelerated and, further, goes into a power-law expansion mode without acceleration corresponding to Friedmann solutions.

In most cosmological models, the geometric description of the universe is based on the Friedmann-Robertson-Walker (FRW) homogeneous isotropic space (space-time) model, which is associated with a high degree of isotropy of space, measured on the basis of the cosmic microwave background (CMB) radiation research. This identification also relies on a formal result known as the Ehlers-Geren-Sachs theorem, which refers to the universe filled with any ideal barotropic fluid [12].

The metric of Friedmann-Robertson-Walker (FRW) space-time is written as follows:

$$ds^2 = -dt^2 + a^2(t)\left(\frac{dr^2}{1 - kr^2} + r^2\left(d\theta^2 + \sin^2\theta d\varphi^2\right)\right) \tag{1}$$

where $a(t)$ is a scale factor which characterizes the size of the universe, $\{r, \theta, \varphi\}$ are the spherical coordinates, and the values $k = 0$, $k = 1$, and $k = -1$ correspond to a spatially flat, closed, and open model of the universe.

The source of the accelerated expansion of the early universe with the equation of state $p = -\rho$ is a vacuum; the equation of the state $p \approx -\rho$ corresponds to a scalar (bosonic) field. The Bose-Einstein statistics for an ensemble of bosons, in contrast to an ensemble of fermions obeying the Pauli exclusion principle, implies that there can be several particles in one quantum state, which leads to the formation of boson condensate in which the increase in the concentration of massless bosons is associated with a decrease in the effective pressure corresponding to the equation of state $p \approx -\rho$. The initial (quasi) exponential expansion associated with a negative pressure, due to the exotic equation of state, is unstable, which leads to a phase transition, the termination of accelerated expansion, and the fragmentation of the original volume into many areas in which further evolution corresponds to the Friedmann solutions.

Also, the presence of a scalar field violates the symmetry of the system, which leads to the appearance of a mass of initially massless particles, for example, in the Higgs field [9].

Thus, the inclusion of the scalar field into cosmological models makes it possible to move from (quasi) de Sitter solutions to the Friedmann ones.

To prevent the rapid decay of the state of $p \approx -\rho$, it is necessary to assume the existence of some potential barrier, that is, the minimum potential energy of a scalar field. Consequently, in realistic inflation models, the scalar field evolves from a state of “false vacuum” with a non-zero potential energy to a state of “true vacuum,” corresponding to the minimum of a potential $V(\phi)$. In other words, the scalar field rolls down (or tunnels) from some initial state to the minimum of $V(\phi)$, and the nature of this process is determined by the shape of the potential.

At the moment, there are many models of cosmological inflation with different potentials of a scalar field and different specifics of its evolution. A large number of current models of the early universe on the basis of the inflationary paradigm are considered in the review [13].

The physical justification for the inclusion of scalar fields in cosmological models is based on the experimental detection of the Higgs boson in the experiment at the Large Hadron Collider [14]. Thus, the scalar field corresponding to the Higgs bosons can be considered as the source of the gravitational field of the early universe. Moreover, the Higgs field can be considered as “inflation,” leading to early accelerated expansion of the universe.

Now, in the system of units $8\pi G = c = 1$, we write the action that determines the dynamics of a scalar field ϕ based on Einstein’s theory of gravity:

$$S_E = \int d^4x\sqrt{-g}\left[\frac{1}{2}R - g^{\mu\nu}\frac{1}{2}\partial_\mu\phi\,\partial_\nu\phi - V(\phi)\right] \tag{2}$$

where R is the Ricci scalar and $V(\phi)$ is the potential of a scalar field.

From the variation of this action with respect to the metric (1) and a field ϕ, for the case of the spatially flat universe, we obtain the equations defining the dynamics of a scalar field [9]:

$$3H^2 = \frac{1}{2}\dot{\phi}^2 + V(\phi) \tag{3}$$

$$-2\dot{H} - 3H^2 = \frac{1}{2}\dot{\phi}^2 - V(\phi) \tag{4}$$

$$\ddot{\phi} + 3H\dot{\phi} + \frac{dV(\phi)}{d\phi} = 0 \tag{5}$$

where $H = \dot{a}/a$ is the Hubble parameter, $X = \frac{1}{2}\dot{\phi}^2$ is the kinetic energy of a canonical scalar field ϕ, and the dot denotes the derivative with respect to cosmic time $\dot{a} = da/dt$.

Also, the state parameter w of a scalar field can be calculated as

$$w = \frac{p}{\rho} = \frac{X - V}{X + V} = -1 - \frac{2}{3}\frac{\dot{H}}{H^2} \tag{6}$$

To build a consistent model of cosmological inflation, the following conditions must be met:

a. The presence of the stage of accelerated expansion, which implies -1 < w < -1/3

b. The completion of the stage of accelerated expansion w = -1/3

c. The reheating of the scalar field with the subsequent formation of photons, i.e., the transition to the stage of predominance of radiation with w = 1/3

Currently, along with other models, several types of cosmological inflationary models are considered, which differ in both by the type of potential and the initial conditions under which an inflationary stage occurs: namely, a scalar field can be located at one of its potential minima, or accelerated expansion occurs for any conditions permitting the onset of inflation for scalar field energy density values comparable to the Planck mass [9].

The form of the scalar field's potential is determined from the physics of elementary particles and theories of the unification of fundamental interactions, such as supersymmetric theories and string theories in the context of the inflationary paradigm. Physical mechanisms corresponding to a large number of inflationary potentials were discussed in the review [14]. Due to the fact that the potential of the scalar field has a great importance for determining the physical processes at the stage of cosmological inflation, the potential $V(\phi)$ is given to build models of the early universe.

However, the finding of exact solutions to the system of Eqs. (3)–(5) for a given potential is impossible in most cases due to their nonlinearity. For this reason, a convenient tool for analyzing inflationary models based on a given scalar field potential is the "slow-roll approximation" which implies that $V(\phi) >> X$ and $\ddot{\phi} \approx 0$ and, therefore, simplifies the initial dynamic equations [9].

The dynamics of the expansion of the universe which determined by the scale factor $a(t)$ is no less important when analyzing cosmological models. By setting the expansion law $a(t)$, it is often possible to find the exact solutions of the system of Eqs. (3)–(5) and restore the evolution of the scalar field $\phi(t)$ and the potential $V(\phi)$. The different methods for constructing exact and approximate solutions of the equations of cosmological dynamics (3)–(5) can be found, for example, in the papers [15, 16]. We also note that the system of Eqs. (3)–(5) has many solutions that satisfy all the conditions for the inflationary stage that were outlined earlier.

Now, we consider the parameters that are necessary for the analysis of inflationary stage, namely, the e-fold number and the slow-roll parameters.

The e-fold number is usually noted as the natural logarithm of the ratio of the scale factor at the end of inflation to the scale factor at the beginning of inflation [9]:

$$N(t) = \ln \frac{a(t_{end})}{a(t_i)} = \int_{t_i}^{t_{end}} H dt \tag{7}$$

where t_i and t_{end} are the times of the beginning and ending of the inflation. The value of the number of e-folds at the end of the inflationary stage is estimated as $N = 50 - 60$ [9].

When analyzing inflationary models, the slow-roll parameters are important, and these parameters are defined as follows [13]:

$$\epsilon \equiv 2\left(\frac{H'_\phi}{H}\right)^2 = -\frac{\dot{H}}{H^2} \tag{8}$$

$$\delta \equiv 2\frac{H''_\phi}{H} = \epsilon - \frac{\dot{\epsilon}}{2H\epsilon} = -\frac{\ddot{H}}{2H\dot{H}} \tag{9}$$

$$\xi \equiv 4\frac{H'_\phi H'''_\phi}{H^2} = \frac{1}{H}\left(\dot{\epsilon} - \dot{\delta}\right) \tag{10}$$

Based on the relations (8)–(10), one can consider the slow-roll parameters as a function of time or field. During the inflationary stage, $\epsilon < 1$ and its completion are determined by the condition $\epsilon = 1$.

3. Cosmological perturbations

Cosmological perturbations are the source of the evolution of large-scale structure of the universe. An explanation of the distribution of galaxies and clusters of galaxies at large distances in the observable part of the universe on the basis of cosmological perturbations was originally proposed in the works of Harrison [17] and Zeldovich [18]. In the context of inflationary paradigm, the source of cosmological perturbations is quantum fluctuations of a scalar field and the corresponding fluctuations of the metric, which, in a linear order, correspond to three modes that evolve independently.

It is known from the classical theory of cosmological perturbations that the analysis of metric inhomogeneities can be simplified to the study of one perturbed quantity [11]. Thus, the quantum theory of cosmological perturbations can be reduced to the quantum description of the fluctuations of a certain scalar field.

Since the background in which the scalar field evolves depends on time, the field mass will also depend on time. This dependence of the field's mass on time will lead to the appearance of particles if the evolution begins with a certain vacuum state. Quantum particle production corresponds to the development and growth of cosmological perturbations.

In inflation models with one scalar field, at the crossing of the Hubble radius, cosmological perturbations "freeze," and their quantum state begins to change in such a way that the condition of constant amplitude is satisfied. The freezing of the vacuum state leads to the appearance of the classical properties [11]. Thus, the theory of cosmological perturbations provides a consistent approach for considering the generation and evolution of cosmological perturbations.

The influence of cosmological perturbations on the anisotropy and polarization of the background radiation is determined on the basis of spectral parameters and observational restrictions on the values of which form the basis of the experimental verification of theoretical models of the early universe. Also, within the framework of the cosmological perturbation theory, it is possible to calculate the spectra of initial density perturbations and relic gravitational waves depending on the values of the parameters of theoretical models [11].

After the end of the inflationary stage, the scalar field reheating and the formation of the first light particles of baryon matter begin. In the hot dense plasma, due to scattering on electrons, photons propagate much slower than the speed of light. When the universe expands so much that the plasma cools down to the recombination temperature, the electrons begin to connect with the protons, forming neutral hydrogen, and the photons begin to spread freely.

The points from which the photons reach the observer form the last scattering surface, whose temperature at the time of recombination is $\sim$3000 K and rapidly decreases with the expansion of the universe. The background radiation temperature is isotropic with an accuracy of 10^{-5}. The low anisotropy manifests itself as the temperature difference in different directions and its value is approximately equal to 3 mK [10].

The kinetic component of the anisotropy of the cosmic background radiation is due to the movement of the observer relative to the background radiation, which corresponds to the dipole harmonic.

In addition to the kinetic component in the anisotropy of the CMB, there are potential terms associated with effects in gravitational fields of very large scales that are comparable to the distance to the last scattering surface, namely:

a. Sachs-Wolfe effect, which corresponds to a change in the photon energy in a variable gravitational field of the universe

b. Silk effect due to adiabatic compression of radiation and baryon acoustic oscillations prior to the recombination epoch in high- and low-density zones

In the zero order of the cosmological perturbation theory, the universe is described by a single function of time, namely, by the scale factor $a(t)$. In the first (linear) order, the perturbations of the metric are the sum of three independent modes—scalar, vector, and tensor (relic gravitational waves), each of which is characterized by the spectral function of the wave number k [11].

For the inflationary stage in the linear approximation, one can write the Mukhanov-Sasaki equations for Fourier modes of the scalar v_k and tensor u_k perturbations [11]:

$$\frac{d^2 v_k}{d\eta^2} + \left(k^2 - \frac{1}{z}\frac{d^2 z}{d\eta^2}\right) v_k = 0 \tag{11}$$

$$\frac{d^2 u_k}{d\eta^2} + \left(k^2 - \frac{1}{a}\frac{d^2 a}{d\eta^2}\right) u_k = 0 \tag{12}$$

where $z = a\dot{\phi}/H$, k is a wave number, and η is the conformal time.

Eqs. (11) and (12) allow finding the power spectra $\mathcal{P}_S$ and $\mathcal{P}_T$ and spectral indices n_S and n_T of the scalar and tensor perturbations. The formulas for calculating the main cosmological parameters at crossing the Hubble radius $(k = aH)$ [19] are

$$\mathcal{P}_S(k) = \frac{1}{2\epsilon}\left(\frac{H}{2\pi}\right)^2 \tag{13}$$

$$\mathcal{P}_T(k) = 2\left(\frac{H}{2\pi}\right)^2 \tag{14}$$

$$n_S - 1 = 2\left(\frac{\delta - 2\epsilon}{1 - \epsilon}\right) \tag{15}$$

$$n_T = -\frac{2\epsilon}{1 - \epsilon} \tag{16}$$

$$r = \frac{\mathcal{P}_T}{\mathcal{P}_S} = 4\epsilon \tag{17}$$

The data on the effects of scalar and tensor modes can be obtained from observations of the anisotropy and polarization of the cosmic microwave background (CMB) radiation, which arose as a result of the joint effect on the photon distribution of the perturbation modes. Observational restrictions on the values of the parameters of cosmological perturbations according to the data of the PLANCK are [10]

$$10^9 \mathcal{P}_S = 2.142 \pm 0.049 \tag{18}$$

$$n_S = 0.9667 \pm 0.0040 \tag{19}$$

$$r < 0.065 \tag{20}$$

In the context of such verification of cosmological models, let us pay attention to the tendency for the upper limit to decrease by the value of the tensor-scalar ratio for updated observational data [10].

Also, we note that the relic gravitational waves were not directly observed, which leads to a large number of theoretical models of cosmological inflation, which provide an explanation of the origin and evolution of the large-scale structure of the universe and correspond to the observational constraints.

4. Generalized exponential power-law inflation

The scheme for constructing models of the early universe based on the evolution of the scalar field in the context of the inflationary paradigm can be represented as follows:

a. The generating solutions of background dynamic equations (excluding quantum fluctuations of the scalar field) for a given potential, the law of accelerated expansion of the early universe, or the evolution of a scalar field.

b. Analysis of the quantum fluctuations of a scalar field and the corresponding metric perturbations on the basis of the theory of cosmological perturbation for the previously obtained background solutions. The result of this analysis is the values of the spectral parameters of cosmological perturbations which can be calculated from Eqs. (13)–(17).

c. Comparison of the obtained spectral parameters of cosmological perturbations with the corresponding observational data (18)–(20).

To build cosmological models corresponding to observational data, we propose the principle of constructing the inflationary models with generalized exponential power-law expansion. For this aim we consider any exact solutions $\{\phi, H, V\}$ of Eqs. (3)–(5) for which the substitution of the slow-roll parameters (8)–(10) into Eqs. (13)–(17) doesn't correspond to observational constraints (17)–(18).

After the following transformations

$$\overline{H} = nH + \lambda \tag{21}$$

$$\overline{a}(t) = Ca^n(t)e^{\lambda t}, C = \overline{a}_0/a_0^n \tag{22}$$

$$\varphi = \sqrt{n}\phi \tag{23}$$

$$\overline{V}(\phi) = 3n^2H^2 + 6\lambda nH - nH'^2_\phi + 3\lambda^2, \overline{V}(\varphi) = \overline{V}(\phi(\varphi)) \tag{24}$$

one has new exact solutions $\{\varphi, \overline{H}, \overline{V}\}$ with new slow-roll parameters

$$\overline{\epsilon} = n\epsilon\left(n + \frac{\lambda}{H(\epsilon)}\right)^{-2} \tag{25}$$

$$\overline{\delta} = \delta\left(n + \frac{\lambda}{H(\epsilon)}\right)^{-1} \tag{26}$$

and with the conformity to observational constraints which can be achieved by choosing the values of free constant parameters n and λ.

The proposed approach has two limitations:

a. The original scale factor $a(t)$ doesn't violate the law of accelerated expansion.

b. The potential $\overline{V}(\varphi)$ corresponding to the scale factor (20) implies the evolution of the scalar field φ, according to the inflationary paradigm.

Transformations (21)–(24) define a class of models with the generalized exponential power-law dynamics, and the original scale factor $a(t)$ may not correspond to the condition of accelerated expansion $\ddot{a}>0$; however, the resulting scale factor $\overline{a}(t)$ implies a combination of the de Sitter solution (for $n = 0$) and the power-law expansion (for $\lambda = 0$), which corresponds to the basic feature of the inflationary paradigm implying a graceful exit from the stage of accelerated expansion to the power-law non-accelerated expansion.

5. Relic gravitational waves

As an additional verification tool for cosmological models, we consider the possibility of direct detection of the relic gravitational waves. The detection of relic gravitational waves is extremely important for determining the parameters of the models of early universe. Additionally, such a detection enhances the position of the inflationary paradigm compared to alternative scenarios, for example, the models with a rebound from singularity in which cosmological gravitational waves are absent [19].

As the main observational characteristic of relic gravitational waves, we consider the energy density, which is usually determined by the dimensionless quantity [20]:

$$\Omega_{GW}(f) = \frac{1}{\rho_c}\frac{d\rho_{GW}}{d\ln f} \tag{27}$$

where f is the linear frequency, $\rho_c = 3H_0^2$ is the critical energy density, H_0 is the value of the Hubble parameter in the modern era, and ρ_{GW} is the energy density of gravitational waves.

Also, the energy density of relic gravitational waves can be represented in terms of the power spectrum:

$$\Omega_{GW}(k) = \frac{k^2}{12H_0^2}P_T(k) \tag{28}$$

The frequency and energy density of relic gravitational waves are limited by the following conditions [20]:

a. The energy density of relic gravitational waves should not exceed

$$\int_{f_0}^{\infty}\Omega_{GW}d\ln f < 1.1\times 10^{-5} \tag{29}$$

where $f_0 \approx 10^{-9}$ Hz.

a. The temperature of the scalar field T_* and the frequency of gravitational waves f at the end of the inflation stage are

$$T_* = 5.85\times 10^6\left(\frac{f}{Hz}\right)\left(\frac{g_*}{106.75}\right)^{1/6} GeV \tag{30}$$

$$f = 1.71 \times 10^{-7} \left(\frac{T_*}{GeV} \right) \left(\frac{g_*}{106.75} \right)^{-1/6} Hz \tag{31}$$

where g_* is the effective number of the degrees of freedom (in standard model of elementary particles $g_* = 106.75$).

Therefore, conditions (18) and (21)–(23) impose restrictions on the parameters of relic gravitational waves.

The application to the analysis of the models of the early universe only of the slow-roll approximation implies a low-frequency spectrum of relic gravitational waves in the range of $10^{-18} - 10^{-16}$ Hz [20]. However, the predominance of the kinetic energy of the scalar field during the evolution of the early universe provides a theoretical justification for the existence of high-frequency relic gravitational waves in models with one scalar field in the range of $10^2 - 10^4$ Hz [21] which can be used as affordable means of verification of models of the early universe in the presence of physical effects that increase the sensitivity of the detector to the required level.

Currently, the most productive method of direct detection of gravitational waves is the use of interferometers as detectors, which was proposed in the article by Gertsenshtein and Pustovoit [22]. This principle is widely used in modern laser interference gravitational antennas, the main element of which is the Fabry-Perot interferometer. These are broadband gravitational antennas, which offer a lot of opportunities as to the methods of recording of gravitational waves and extracting signals, as well as the use of quantum non-perturbative measurements and the inclusion of gravitational antennas in the network. The main element of laser interference gravitational antennas, as a rule, is Fabry-Perot multipath free-mass resonator, on whose properties the sensitivity and noise immunity of the entire gravitational antenna largely depend [4, 23, 24].

After creating the first laser interferometer for detecting gravitational waves, systematic work began on the creation and improvement of such devices in various laboratories around the world. The experience of gravitational antenna projects by VIRGO (Italy, France), LIGO (USA), TAMA (Japan), CLIO (Japan), GEO-600 (Germany), and OGRAN (Russia) will certainly be used to create more compact and highly sensitive antennas of new generation [4]. Also, as the most promising project for the direct detection of gravitational waves, work on the creation of a space interferometer in a helio-stationary orbit should be noted, in which the distance between the mirrors will be about 1 million kilometers. This project is called Laser Interferometer Space Antenna (LISA) [25]. The implementation of the LISA project is scheduled for 2029.

One of the promising methods for increasing the sensitivity of gravitational antennas in the high-frequency region of the spectrum is to use the phenomenon of low-frequency optical resonance, which distinguishes this approach from other projects on the detection of gravitational waves. The presence of this effect in Fabry-Perot interferometers was first considered in [23, 24]. At the moment, there is a high-frequency gravitational wave detector, which was built at the University of Birmingham, United Kingdom [26]. Also, it is planned to build the high-frequency gravitational wave detectors in Japan [27].

Thus, at the moment there are a large number of promising methods for direct observation of gravitational waves, which correspond to the ability to measure the characteristics of relic gravitational waves for a better understanding of the physical processes occurring in the early universe.

6. Conclusion

We considered the basis of building and verifying of the inflationary models of early universe. As the method for constructing the exact cosmological solutions corresponding to observational constraints, the models with generalized exponential power-law dynamics are proposed.

The verification of the relevance of such models is related to the estimation of the contribution of relic gravitational waves to the anisotropy and polarization of the cosmic microwave background radiation. Therefore, there are a lot of inflationary models with different scalar field potentials that will satisfy the observational constraints.

The most obvious way to significantly reduce the number of theoretical models of cosmological inflation is direct detection of relic gravitational waves.

The most promising methods in this area of experimental research are using the interferometers as detectors. The interesting direction of the observation is the detection of high-frequency relic gravitational waves using the effect of low-frequency optical resonance proposed in [23, 24].

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