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Editorial

Centenary of Alexander Friedmann's Prediction of Universe Expansion and the Prospects of Modern Cosmology

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Abstract: In this Editorial to the Special Issue "The Friedmann Cosmology: A Century Later", we consider an outstanding character of Friedmann's prediction of Universe expansion, which laid the foundation of modern cosmology. The list of the main discoveries made in cosmology during the last one hundred years is followed by a formulation of the standard cosmological model. The articles contributing to the Special Issue are considered in relation to this model, and to several alternative theoretical approaches. Special attention is paid to unresolved problems, such as the nature of dark matter and dark energy, Hubble tension and the pre-inflationary stage of the Universe evolution. The conclusion is made that astrophysics and cosmology are on the threshold of new fundamental discoveries.

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1. Introduction

In this Editorial to the Special Issue "The Friedmann Cosmology: A Century Later", we analyze the role played by the fact that our Universe is expanding in the modern picture of the World, briefly list the main discoveries made in cosmology and astrophysics of the expanding Universe during the last 100 years, and characterize the topics of the contributing articles. Special attention is paid to the main unresolved problems and different approaches to their resolution.

Alexander Friedmann made his famous prediction that the Universe expands with time, starting from a point called the cosmological singularity, in his article [1] published in 1922 for the case of finite space volume. In 1924, he obtained the same result [2] for the Universe possessing an infinitely large spatial volume, which is the case for our Universe according to modern astronomical observations. Friedmann obtained his results by solving Einstein's equations of the general theory of relativity with no additional assumption that the obtained model of the Universe should be static. In this way, he acted as a mathematician by looking for what is contained in the fundamental equations of the general theory of relativity, whether or not this is in agreement with the concepts of Ptolemy, Copernicus, and Newton, who believed that the Universe is static. Note that in the article [1] the author name was written as A. Friedman, but Albert Einstein, in his note [3] (which he later recognized as mathematically mistaken), cited [1] as written by A. Friedmann. In the second article on cosmology [2], Alexander Friedmann used just this version of his name in the Latin alphabet, which became commonly accepted over a century.

Before Friedmann, the cosmological solutions to Einstein's equations with the cosmological constant were obtained by Einstein himself [4] (the static solution) and de Sitter [5] (the empty Universe). However, it was Friedmann who demonstrated that, for the homogeneous and isotropic space, even in the presence of an additional cosmological term in Einstein's equations, the static solution arises in only one exceptional case.

Friedmann's papers [1,2] laid the foundation of modern cosmology. Although during the first years after publication his results were unnoticed, they were later rediscovered by Lemaître [6], Robertson [7], and Walker [8]. More importantly, the Universe expansion should manifest itself as moving of all galaxies away from an observer on the Earth, leading to the redshift of light emitted by them. This effect was systematically studied by Lemaître [6] and Hubble [9] as an experimental confirmation of the Universe expansion.

In the next decades, the development of modern cosmology was marked by a formation of the theory of the Hot Universe, which is also often called the Big Bang Universe, developed by Gamov [10]. In the framework of this theory, Gamov and his collaborators explained the origin of physical elements in the process of primordial nucleosynthesis [11] (see also the modern review [12]). A big success of the theory of the Hot Universe was the prediction [13], and subsequent discovery in 1965 [14], of the relic radiation or cosmic microwave background radiation. This discovery can be considered as a final confirmation of the Big Bang theory and, in particular, of the Friedmann prediction that the initial state of the Universe evolution is the cosmological singularity. Later on, a lot of papers have been published about the properties of relic radiation and its interaction with electrons and the intergalactic medium (see Refs. [15–19] for reviews). On the theoretical side, it was shown [20,21] that any solution of Einstein's equations describing the Big Bang possesses the initial singularity.

The theory of the Hot Universe does not describe the very early stages of its evolution below and just after the Planck time, where the quantum effects come into play. Thus, an application of the standard general theory of relativity to the period down to cosmological singularity results in serious problems. One of them, called the horizon problem, states that at Planck time the Universe should consist of about 10^{89} causally disconnected parts, in contradiction with the fact that the relic radiation has the same temperature in all points and in all directions.

The problems in the description of the evolution of the Universe near the cosmological singularity were partially solved by the model of inflation proposed in the beginning of 1980s. According to this model, the initial expansion of the Universe goes on exponentially fast. This happens under the influence of either the so-called inflaton scalar field [22–28] or the vacuum polarization effects of quantized fields [29,30]. According to the model of inflation, the usual elementary particles were created during the period of reheating after the end of the exponentially fast expansion, when the inflaton field oscillated near the minimum of its potential [28,31,32]. The theory of reheating is based on the effect of the exponential growth of the number of boson pairs created from vacuum by the periodic in time fields [33,34]. It was elaborated on by many authors [35–46].

One more great discovery in the physics of the expanding Universe was made in 1998, when two groups of researchers [47,48] working with the redshift data of supernovae in binary systems arrived to the conclusion that the expansion of the Universe is accelerating. This result could be explained by the existence of a new form of matter, which constitutes of approximately 68% of the Universe energy and was called dark energy. As opposed to usual and dark matter, dark energy is characterized by negative pressure (see Ref. [49] for a review). There are many models of dark energy proposed in the literature, describing it using the cosmological constant [50], classical scalar field called a quintessence [51,52], scalar–tensor gravity [53–55], and hypothetical elementary particles, whose properties depend on the density of matter in the environment [56–58].

2. The Standard Cosmological Model

Friedmann's seminal works [1,2] and further developments described in the previous section lie into the basis of the ΛCDM model, which is the standard model of contemporary cosmology (see, for example, Ref. [59]). Here, Λ is the cosmological constant, and the abbreviation CDM for the cold dark matter means that this form of matter, which contributes approximately 28% of the Universe's energy, is assumed to consist of non-relativistic particles (e.g., of axions [60,61]). This model assumes that the general theory of relativity is the correct theory of gravity on cosmological scales, and the space-time geometry of the homogeneous and isotropic expanding Universe is described by the Friedmann metric (see

Section 2 of Ref. [62] belonging to this Special Issue, where the Friedmann equations and their solutions possessing the cosmological singularity are presented and discussed in the cases of closed, open, and quasi-Euclidean spaces).

As a result, the ΛCDM cosmological model provides a reasonably good account of (i) the existence and structure of the cosmic microwave background; (ii) the large-scale structure in the distribution of galaxies; (iii) the observed abundances of hydrogen (including deuterium), helium, and lithium; and (iv) the accelerating expansion of the Universe, observed in the light from distant galaxies and supernovae.

The ΛCDM model became the leading cosmological model following the observations of accelerating expansion in 1998 [47,48], and was quickly supported by other observations. Thus, in 2000, the BOOMERanG microwave background experiment measured the total (matter–energy) density to be close to 100% of the critical one [63], whereas in 2001, the 2dFGRS galaxy redshift survey measured the matter density to be near 25% [64]. The large difference between these values supports a positive value of Λ describing the dark energy. Much more precise spacecraft measurements of the microwave background from WMAP in 2003–2010 [65] and Planck in 2013–2015 [66,67] have strongly supported the standard cosmological model, and pinned down the values of its parameters, most of which are now constrained below 1 percent uncertainty.

The enormous success of observational cosmology, achieved in the last 30 years, especially the final results of the cosmic Planck mission that appeared in 2018, have successfully confirmed those previously put forward and developed cosmological theoretical ideas about the history of the Universe as its passage in the past through the stage of the hot Big Bang (including primary cosmological nucleosynthesis, recombination and generating anisotropy and polarization of the cosmic microwave background radiation). Also, it was proved that the Universe had a cold quasi-de Sitter (inflation) epoch, during which spatial inhomogeneities of the matter distribution were formed due to the quantum gravitational effects. In fact, galaxies and all compact objects were formed from these primordial inhomogeneities. Moreover, the physical properties of the effective sort of matter, which supported the inflation on the earlier epochs of the Universe evolution, are similar from the qualitative point of view to the properties of the dark energy in the late-time Universe (it seems to be reasonable to indicate this cosmic substratum as a primordial dark energy).

No less fundamental results have been achieved in astrophysics of compact relativistic objects, namely black holes and neutron stars. Specifically, the mass of the supermassive black hole in the center of our Galaxy (the object Sgr A*) was measured exactly by the motion of nearby stars around it. Next, the observational picture of the shadow of a supermassive black hole in the M87 galaxy was obtained, and the processes of merging of black holes and neutron stars in binary systems have been discovered and investigated using the gravitational (and electromagnetic, in the latter case) radiation from them. Finally, it has been observed that the velocity of gravitational waves coincides with that of light with a great accuracy.

Below, we briefly list the articles included in this jubilee Special Issue devoted to the centenary of Friedmann's cosmology in their relation to the standard cosmological model and some research directions beyond them.

3. Current Research Topics in Cosmology

We start with several articles that are devoted to a few novel aspects of the general theory of relativity. All of them use the theoretical formalism belonging to the standard cosmological model, but deal with some nonstandard situations and exotic forms of matter. Thus, Ref. [68] considers particles of negative and zero energy, which can exist inside the horizon of a Schwarzschild black hole, and in Miln's and Gödel's cosmological models. The situations of this kind have already been considered previously [69–71], but here they arise in especially simple and widely used cases. Another article of this Special Issue [72] investigates the properties of traversable wormholes, which can be determined in the closed Friedmann Universe by the dust-like matter. The solutions of Einstein's equations of such type were considered in the literature [73–78], but some exotic kinds of matter were used as their source (e.g., the so-called phantom scalar field).

The article [79] suggests an expression for the generalized entropy depending on four parameters which contains all the known entropies considered so far (see, for example, refs. [80–83]) as particular cases. It is shown that by adding the scalar field with a power-type potential one obtains a viable model of inflation consistent with the Planck data. The next article of the Special Issue considers an isotropization of the Kantowski–Sachs cosmological model with radiation and a running cosmological constant energy density [84]. Previously this effect was investigated in the Kantowski–Sachs model without taking the running cosmological constant into account (see, e.g., refs. [85–90]). It is shown that in some cases the effect of running leads to a quicker isotropization.

Article [91] demonstrates that it is possible to construct the non-singular cosmological model for the spatially flat Friedmann Universe if taking the phantom and tachyon scalar fields into account. This is in line with previous attempts to find the non-singular cosmological models and black holes (see Refs. [92–95] for a review). Another article [96] investigates the phase transitions of the physics of elementary particles, which can occur during the collisions of particles near the horizons of black holes. Specifically, the transition between quark–gluon plasma and hadrons, the electroweak and the grand unification phase transitions are considered [28,97–99]. The back reaction of the energy density of phase transitions on the space-time metric is investigated. One more article [100] studies the evolution of the Friedmann cosmological model under an impact of the nonlinear spinor field.

Several articles belonging to this Special Issue deal with different non-Einsteinian theories of gravitation, including teleparallel gravity [101–103]. Strictly speaking, the formalisms used in these articles are beyond the standard cosmological model. Thus, in [104], which deals with the alternative theories of gravitation, the two variants of teleparallel gravity are considered. It is shown that the corresponding cosmological models are, in fact, the same as in Einstein's general theory of relativity. This makes the choice between them the subject of convention [105,106].

One more article [107] published in this Special Issue is devoted to the elaboration of a new, improved model on inflation in the framework of $F(R)$ modified gravity, where R the scalar curvature of space-time. The theories of this kind are often considered in the literature (see, e.g., refs. [108–110]). They are, in fact, equivalent to the scalar–tensor theories of gravity [109,111]. It is shown that the obtained model demonstrates a very good agreement with the measurements of relic radiation. The scalar–tensor theories of the Brans–Dicke class [112–114] are also applied in another paper belonging to this Special Issue [115] for the construction of a cosmological model with a constant scale factor, which reproduces some properties of the standard cosmological model. The homogeneous isotropic cosmological model, which demonstrates a transition from the decelerated expansion in the past to the present acceleration, is constructed in ref. [116] on the basis of $F(R, T)$ modified gravity theory, where T is the trace of the stress–energy tensor of matter. The alternative theories of gravitation of this kind have often been considered in the literature in recent years [117–120].

Two more articles using the alternative theories of gravity are devoted to a new analytically solvable isotropic cosmological model [121] and to the model of primordial black holes determined by field fluctuations in extra dimensions [122]. The first of these articles [121] uses the so-called extended Einstein-aether-axion theory [123,124] and considers the homogeneous Universe filled with axionic dark matter. The second article [122] uses the formalism of $f(R)$ gravity and investigates the possibility that some supermassive black holes may originate from a collapse of the domains of dark energy with extremely high energy density, caused by the quantum fluctuations of the minimally coupled scalar field in the compacted inner space (see ref. [125] for a review on the primordial black holes).

Several further articles published in this jubilee Special Issue are devoted to the astrophysics of the Friedmann Universe. Thus, review [126] discusses the role of neutrinos at different stages of the evolution of the Friedmann Universe. This includes the impact of neutrinos on the Universe expansion rate, its chemical and isotopic composition, the anisotropy of relic radiation, and formation of the large-scale structure. Special attention is paid to possible existence of the so-called sterile neutrinos, which are hypothetical neutrino-type particles not possessing the isospin charge and only interacting with other elementary particles gravitationally [127–130].

Article [131] is devoted to the critical discussion of tension concerning the value of the Hubble constant H_0, which is the proportionality coefficient between the proper distance to the remote galaxy and the speed of its separation. Although, in the standard cosmological model, the value of H_0 is expressed via the main parameters of this model, different approaches to its measuring [66,132] result in the values that do not overlap, leading to a 5σ tension. The extensive literature devoted to the H_0 tension discussed in ref. [131] did not bring a resolution to this problem yet.

The physical nature of dark energy is still unknown, and there are many theoretical approaches to its understanding, which are reviewed in ref. [133]. These are the most common approach describing the dark energy by means of the cosmological constant, as well as the approaches using the concept of a quintessence and scalar–tensor modifications of the general theory of relativity, exploiting the chameleon, symmetron- and environment-dependent dilaton fields and corresponding hypothetical particles. In fact, only the description of dark energy in terms of cosmological constant is in the frames of the standard cosmological model, whereas all others are beyond it. There are many experimental tests for the hypothetical constituents of dark energy. One of them is based on measuring the Casimir force between two closely spaced macrobodies, which should be modified by the presence of dark energy. This approach already significantly strengthened the constraints on axions as the hypothetical constituents of dark matter [134–137]. In the case of dark energy, however, the problem is more complicated because the respective interaction potentials are not fixed uniquely, but are different in different models [138–140].

The theoretical aspects of wormhole solutions of Einstein's equations are discussed in many papers (see Ref. [72] belonging to this Special Issue, mentioned above). To the present time, however, wormholes were not observed, in spite of the fact that some authors tried to find their observational features [141–144]. In this Special Issue, it was suggested [145] that one should consider the acceleration of matter into a wormhole possessing a monopole magnetic field. It is shown that the resulting spectrum is characterized by some unique features, which allow for distinguishing it from the spectrum of, e.g., a Kerr black hole.

The next group of articles published in this Special Issue is devoted to some quantum aspects of cosmology. These articles can be naturally divided into two subgroups. The first one considers the quantum effects on the background of classical curved space-time, whereas the second one deals with the quantization of gravitation, i.e., with quantum gravity. We begin with the articles belonging to the first group.

The most well-known quantum effect occurring in the expanding Friedmann Universe is the creation of particles of matter fields from the vacuum state. This effect is discussed in [62]. It is considered in comparison to similar effects occurring in an external electromagnetic field. The creation of particle–antiparticle pairs in the homogeneous isotropic models of the Universe plays the most important role in the early stages of its evolution. Thus, it plays a decisive role in the process of reheating after inflation, i.e., during the period of time when all of the standard elementary particles have been created [32]. There are different methods used in the theoretical description of the particle creation in the external gravitational field. One of them uses the concept of adiabatic particles [146,147], while another one is based on the diagonalization of the Hamiltonian of a quantized field [148–150].

One more (phenomenological) method describing the effect of particle creation in the Riemannian space-time is suggested in [151] published in this Special Issue. For this purpose, the action of an ideal fluid in Euler's variables is used, where the conservation law for the number of particles is replaced with the creation law [152,153].

An important quantum process is the conversion of gravitons to photons and vice versa in the presence of an external magnetic field. This process was considered by several authors in flat space-time (see, e.g., refs. [154–156]). It is, however, of much importance in applications to the relic gravitational waves produced at the inflationary stage of the Universe's evolution in the primordial magnetic field, where the space-time geometry was essentially non-Euclidean. Just this case is investigated in [157], which is included in the jubilee Special Issue, where the transformation between gravitons and photons in the presence of a magnetic field is considered in curved space-time. Next, the results obtained for an arbitrary metric are simplified for the case of the Friedmann Universe. In so doing, the gravitational waves are considered as small perturbations of the background space-time. It is shown that the conversion effect is present only if the electromagnetic wave vector is perpendicular to the magnetic field. An important conclusion is made that the effect of conversion of gravitons into photons in the primordial magnetic field cannot significantly diminish the amplitude of relic gravitational waves.

One more article of this Special Issue [158] investigates the motion of a quantum particle in the Cornell potential on the background of an open Friedmann cosmological model. This subject is of evident interest because this potential was used earlier to ensure the confinement of quarks inside both mesons and hadrons [159]. It is shown that, due to the space curvature, the Cornell potential becomes a potential well of finite depth, making both the bound and scattering states possible.

Finally, one more article devoted to the quantum effects in curved space-time considers the mathematical aspects of quantum field theory in the de Sitter and anti-de Sitter space-times [160]. In this article, it is shown that the correlation functions of quantum scalar field in Minkowski, de Sitter, and anti-de Sitter space-times have some similarities (see the previous results on this subject [161–163]).

The second subgroup of articles devoted to quantum aspects of cosmology deals with the quantization of gravitational field, i.e., with quantum gravity. It is common knowledge that, up to the present, there is no satisfactory theory of this kind, in spite of numerous attempts undertaken by many scientists over several decades to construct it (see the monographs and reviews [164–168]). At the same time, there are a few approaches, including the most famous by DeWitt [169–171], which apply the quantum theory of gravitation in the one-loop approximation to description of the Universe in terms of the wave function. Article [172] published in this Special Issue considers the DeWitt boundary condition imposed on the wave function of the Universe. The obtained results might be considered as a first step towards quantum gravity, leading to a non-singular cosmological model.

Another version of quantum gravity, called the Euclidean quantum gravity [173], is used in [174] to construct a new version of the no-boundary initial state of the Universe.

4. Conclusions

In the foregoing, we have considered the fundamental role of Alexander Friedmann's prediction of Universe expansion for modern cosmology, and briefly listed the major achievements in understanding of our Universe and its evolution made during one hundred years after this prediction. This evolution resulted in the formulation of the standard cosmological model ΛCDM, which provides a satisfactory explanation for most of the physical phenomena discovered by the modern astronomy and astrophysics. Many articles published in this Special Issue devoted to Friedmann's prediction of Universe expansion investigate some physical phenomena in the framework of this model.

Though the ΛCDM model, based on the general theory of relativity, Friedmann cosmology and the concept of the cosmological constant are sufficient to explain many available experimental and observational data, new data appear that have no explanation in the framework of this model, such as the Hubble tension and the CMB dipole anisotropy [175]. In addition, ΛCDM has no explicit physical theory for the origin and physical nature of dark matter and dark energy. As a result, it became clear that we are faced with a fundamental alternative today. Numerous attempts undertaken in order to quantitatively understand all modern cosmological discoveries, including primary dark energy (which is found to be unstable) and dark matter, either go beyond the Standard Model of elementary particle physics, modify Einstein gravity, or use a combination of both of these approaches. It has also become timely to make the next step to the past of our Universe, and investigate possible variants of its pre-inflationary history and the artifacts remaining from them. This requires new astrophysical experiments in space and the further elaboration of quantum gravity. As seen from the above, many articles published in this jubilee Special Issue go beyond the standard cosmological model and look for the new approaches to these unresolved problems.

In the near future, one could expect new fundamental discoveries in astrophysics and cosmology that will shed additional light on the structure and evolution of our Universe.

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