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ASTROPHYSICS AND COSMOLOGY

Opening of New Windows to the Early Universe by Means of Multi-Messenger Astronomy (Brief Review)

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The current situation in cosmology and particle physics, which are two closely related fields of fundamental physics, is unique. The Standard Model of particle physics excellently reproduces all existing experimental data except for neutrino oscillations. Similarly, the comparison of the standard cosmological model with astronomical observations indicates that we well understand the evolution of the Universe from its "birth" to the present. However, to understand mechanisms of numerous cosmological phenomena, it is certainly necessary to go beyond the Standard Model. These are primarily the problems of dark matter and dark energy, generation of the baryon asymmetry of the Universe, and the mechanism of inflation expansion. The problem of the appearance of cosmic magnetic fields and the recent problem of the existence of massive black holes whose number in the Universe is much larger than the expected values are among less known, but also very important problems in conventional cosmology and astrophysics. To understand and possibly solve these problems, it is very important to provide deep insight into the Universe and to obtain data on physical processes at the early stages of the cosmological evolution. Multi-messenger observations involving all possible messengers ("windows") provide a powerful tool for this. In addition to conventional detection of electromagnetic radiation in all bands and all types of cosmic rays, the observations of gravitational waves have recently opened a new window. A complex analysis of information obtained from various astronomical data has been performed in our works supported by the Russian Science Foundation (project no. 20-42-09010 "Opening of New Windows to the Early Universe by Means of Multi-Messenger Astronomy"). In particular, the characteristics of cosmic magnetic fields and possible mechanisms of their appearance have been studied and the observed manifestations of primary black holes have been examined using the data on gravitational waves observed at the LIGO/Virgo/KAGRA interferometers.

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1. INTRODUCTION

Astronomical observations of both current and early Universe provide an efficient tool to verify fundamental physics; moreover, they clearly indicate the necessity of new physics beyond the Standard Model. It is very probable that astronomical observations in near future will lead to new fundamental discoveries. In particular, these expectations are supported by the detection of gravitational waves from the merger of binary black holes with masses of ten to hundred solar masses [1], which has become possible in recent years. Our analysis convincingly indicates that primordial black holes can be sources of gravitational waves [2]. The detection of primordial black holes makes it possible to "look" at the early Universe in the time of their formation, which in particular helps us to much deeply understand the evolution of the Universe beginning with a very early prestellar epoch.

The central aim of our work was to study the problems of the origin of cosmic magnetic fields and the possible nature of dark matter, which are two related cosmological problems in our opinion. In the last subject, we focus on an old hypothesis recently becoming popular that carriers of dark matter (partially or completely) are primordial black holes [3, 4]. In this case, the cosmological density of black holes should be very high and their pairs emitting gravitational waves can be formed with a high probability. The conversion of gravitational waves to electromagnetic ones in an external magnetic field will lead to potentially observable electromagnetic radiation bursts, as shown in [5].

A very important theoretical prediction is a lognormal mass spectrum of primordial black holes:

$$\frac{dN}{dM} = \mu^2 \exp\left\{-\gamma \ln^2 \frac{M}{M_0}\right\}. \quad (1)$$

The theory allows one to determine the central mass of the distribution $M_0 \sim 10M_\odot$, where $M_\odot$ is the solar mass [6].

A particular common feature of cosmic magnetic fields and primordial black holes (especially heavy) is that they can be due to processes occurring in the Universe at the post-inflation stage. This circumstance can promote the establishment of the inflation mechanism. In particular, it will distinguish whether the scalar field, i.e., inflaton is responsible for the inflation or the inflation appears due to the modification of the gravitational interaction because the Gilbert–Einstein action is supplemented with an additional nonlinear term R^2, the so-called *Starobinsky inflation* [7]:

$$S = -\frac{M_{\rm Pl}^2}{16\pi}\int d^4x\sqrt{-g}\left[R - \frac{R^2}{6M_R^2}\right], \quad (2)$$

where $M_{\rm Pl} \approx 1.22 \times 10^{19}$ GeV is the Planck mass and M_R is the constant parameter with the dimension of mass. In this case, the amplitude of relic gravitational waves is strongly decreased in agreement with observations. We note that R^2-inflation model is not the only suppressing tensor modes but the general discussion of inflation theories is beyond the scope of this review.

The action term nonlinear in the curvature scalar results in an additional scalar degree of freedom in gravity. This degree of freedom was called *scalaron*. In the theory implemented within modified R^2 gravity, the post-inflation heating of the Universe occurs due to the gravitational production of elementary particles by oscillations of the scalar field. We calculated the production probability of particles and showed that this heating mechanism allows the existence of dark matter particles with the interaction force typical of supersymmetry but with masses much larger than the limit obtained at the Large Hadron Collider (LHC) [8, 9]. We emphasize that the LHC results that possibly exclude supersymmetry at the TeV scale generally forbid the existence of supersymmetry in canonical cosmology at any energy scales above TeV because stable superpartners of conventional particles predicted in supersymmetric theories would have the cosmological energy density significantly above the critical value. However, our results show that supersymmetry in the R^2 theory is possible even at ultrahigh energies. Meanwhile, as mentioned in our works, LHC data do not exclude supersymmetry at TeV energies but only significantly restrict the allowed parameter range. Thus, we presented an alternative variant to "save" supersymmetry.

Currently collected astronomical data, particularly data from Hubble [10–12] and James Webb [13–16] space telescopes, as well as from ALMA (see, e.g., [17]), surprisingly indicate an extraordinary dense population of the early Universe with galaxies and supermassive black holes (quasars) at red shifts of ~10. Furthermore, the number of black holes with masses from fractions of the solar mass to million solar masses in the current the Universe is much larger than that previously expected within the conventional cosmology and astrophysics, see review [18].

Problems of surprisingly high population of the Universe with objects of an unclear origin (possibly black holes) became known much earlier. For example, objects with masses about half of the solar mass, the so-called MACHO, were detected by means of gravitational microlensing [19, 20]. Their number significantly exceeds the possible number of invisible red dwarfs. The MACHO problem was reviewed in, e.g., [21, 22]. In addition, black holes with masses from several tens to hundred solar masses are observed at the LIGO/Virgo/KAGRA interferometers. Finally, supermassive black holes with masses larger than million solar masses (at the centers of almost all galaxies) and black holes with intermediate masses from thousand to hundred thousands of the solar masses were observed. The corresponding observational data were reviewed in [18], where it was concluded that all these black holes are very probable primordial.

It is remarkable that the masses of observed black holes are well described by the lognormal spectrum (1) for primordial black holes. Numerous mechanisms of the production of primordial black holes with strongly different mass spectra were reported. However, we do not analyze here this very extensive research field.

It is known that magnetic fields of about microgauss exist in galaxies and there are serious indications to possible intergalactic magnetic fields up to nanogauss (these problems were discussed in [23]). magnetic fields also exist in all astronomical objects such as planets (the Earth has a magnetic field), stars (from weak magnetic fields in solar-type stars to giant magnetic fields in magnetars), galaxies, and even intergalactic medium, where magnetic fields can hold their primordial properties. Since magnetic fields exist everywhere in the Universe, black holes are in cosmic magnetic fields. These cosmic magnetic fields of various natures can be studied using multi-messenger astronomy. The study of observable manifestations of cosmic magnetic fields and primordial black holes opens a new window to the early Universe (in particular, on the basis of the results reported in [5]).

2. INTERGALACTIC MAGNETIC FIELDS, GAMMA ASTRONOMY, AND HIGH-ENERGY COSMIC RAYS

Strictly speaking, the generation mechanism of large-scale magnetic fields in the early Universe is unknown but the current observation of intergalactic magnetic fields convincingly evidences their existence in the early Universe (see review [23]). Characteristic magnetic field strengths far from the centers of clusters in the current Universe are also unknown but their understanding is very important for, e.g., the search for sources of ultrahigh-energy cosmic rays. Within the study of these subjects, we consider the problem of growth of primordial inhomogeneities in the early Universe and laws of the joint evolution of dark matter, baryons, and magnetic fields.

To this end, we first developed a software code simulating the growth of primordial inhomogeneities in the early Universe following the approach first proposed in [24] and then developed, e.g., in [25]. The developed code reproduces structures in a sphere with a radius of 200 Mpc around our Galaxy with a spatial resolution of 2 Mpc. To follow the matter distribution in the nearest Universe, we used the 2M++ galaxy redshift catalogue. Further, we developed a code that together with the BORG code [26, 27] could also describe the evolution of the baryon component and magnetic fields, reproducing the observed temperatures of interstellar gas and magnetic field strengths in the centers of individual galaxy in the local Universe. The formation of structures in the local cosmological neighborhood and the related magnetic fields was numerically simulated using two approaches.

In the first approach, we analytically simulated magnetic fields under the assumption that seeds of magnetic fields were formed in the early cosmological epoch irrespectively of a particular model. The magnetic field in this case fills the entire Universe. Then, the magnetic field strength decreases with the expansion of the Universe and increases with contrasts of the matter density. There are two different field growth mechanisms. The first mechanism is due to adiabatic compression and is a linear magnetohydrodynamic effect. The resulting magnetic field strength depends on the contrast of the matter density according to a 2/3 power law, is controlled, and can be reconstructed from the known observed matter density distribution. This mechanism dominates in the regions of voids and filaments. Specific magnetohydrodynamic effects such as the nonlinear evolution of Kelvin–Helmholtz instabilities are important in high matter density regions (e.g., in the centers of Galaxy clusters). It is difficult to simulate such effects and the corresponding simulation results can depend on details of a numerical approach. For this reason, we consider here only the adiabatic compression of the magnetic field. The simulation with the BORG code and this approach allowed us to construct a three-dimensional model of the magnetic field corresponding to the observed large-scale structure of a sufficiently large region of the Universe. The results obtained should be valid in low-density regions comprising most of the Universe. The results of this simulation of magnetic fields were used to calculate the sensitivity of gamma-ray telescopes to sufficiently large primordial magnetic fields $B > 10^{-12}$ G. This specifies the typical magnetic field strength in voids beyond rare structures in them and hence coincides with the primordial magnetic field strength in the current epoch. In this case, the spatial resolution of density contrasts is $2.64h^{-1}$ Mpc, where $h \equiv H/(100\ \text{km s}^{-1}\ \text{Mpc}^{-1})$ is the dimensionless Hubble constant. The studied structure extends up to the Mkn 501 galaxy, which is a blazar; i.e., it contains an active core (supermassive black hole) with an outgoing jet of accelerated particles propagating to the Earth. This galaxy is a variable source of gamma rays at a distance of 140 Mpc from the Earth. A turbulent distribution of the magnetic field with a correlation length of about 1 kpc was also assumed. Primordial cosmological magnetic fields with such a small correlation length λ_B appear, e.g., in models with phase transitions [28]. The correlation length of turbulent cosmological magnetic fields in the current Universe satisfies the evolution relation $\lambda_B \sim 0.1[B/(10^{-12}\ \text{G})]$ kpc [29]. At the same time, the magnetic field generated in the inflation epoch can have a very large correlation length up to the current Hubble scale [30].

The second approach combines the BORG numerical simulation of the large-scale structure and the numerical simulation of magnetohydrodynamics with the RAMSES code [31], which one of the best currently existing magnetohydrodynamic (MHD) codes, adapted to our problem and to existing software. A cubic region with a side of 100 Mpc around the Mkn 501 source including a large void containing the Mkn 501 blazar, which is an active galaxy, and surrounding structures was simulated. magnetic field maps were obtained with various initial conditions, which were specified at a sufficiently large redshift, in the linear epoch for cosmological perturbations. Together with our French colleagues, we also plotted realistic three-dimensional magnetic field maps in the entire space taking into account voids and filaments. The maps were plotted using the RAMSES-MHD code [32] with BORG initial conditions, which enables the reproduction of the positions of all large structures and clusters in the local Universe region with a radius of 200 Mpc around the Galaxy. Thus, these maps could be used for the gamma-ray astronomy study of the magnetic field [33, 34].

The propagation of gamma rays in the cosmological medium results in the development of electromagnetic cascades. These processes are of key importance to interpret gamma-ray astronomy data. In [35], the simulation accuracies of electromagnetic cascades in intergalactic space by CRbeam [36, 35], CRPropa 3.1.7 [37], and ELMAG 3.0.2 [38] open-access Monte Carlo codes were compared in detail. After the elimination of found errors, new CRPropa 3.2 and ELMAG 3.0.3 code versions were released and all three codes applied to simulate nearby sources with redshifts of $z \sim 0.1$ demonstrate agreement within an accuracy of 10%.

The possible presence of the primordial magnetic field in the recombination and reionization epochs can resolve contradiction between different measurements of the Hubble constant and σ_8 [39] and can explain a reduced transparency for the 21-cm line at redshifts $15 < z < 20$ [40]. Such a magnetic field can currently remain in voids of the large-scale structure. Within the mechanism proposed in [39], the extragalactic magnetic field strength in voids is currently 1–10 pG. On the other hand, data from the nowadays HESS, MAGIC, and VERITAS Cherenkov telescopes in combination with data from the Fermi-LAT telescope already exclude magnetic fields weaker than about 10^{-15} G in voids [41, 42]. The possibility of the detection or exclusion of stronger magnetic fields by observing the nearest blazar with a hard spectrum by the next-generation Cherenkov Telescope Array (CTA) observatory was analyzed in [33], where it was demonstrated that gamma-ray observations will allow the detection of magnetic fields of 10^{-14}–10^{-11} G. Thus, the combination of restrictions from microwave cosmic background and from gamma rays from blazers [33, 39, 40] will in future cover the entire range 10^{-15}–10^{-9} G of possible cosmological magnetic fields and will make it possible to verify the hypothesis of their relation to current magnetic fields and their effect on the recombination and reionization epochs.

The possibility of detecting cosmological magnetic fields generated in the inflation epoch using CTA observatory data was also examined in [33]. The corresponding magnetic field has a large correlation length, which leads to the characteristic angular asymmetry of secondary gamma rays correlated between various celestial sources. A necessary condition for the reliable detection such magnetic fields with strengths of 10^{-14}–10^{-12} G is a sufficient brightness of a gamma-ray source at energies above 30 TeV. In this case, the local structure around the source becomes significant and can strongly weaken a cascade signal. The choice of the local structure near sources and the selection of blazars appropriate for the detection of inflation magnetic fields were performed using our plotted realistic magnetic field maps. Our analysis showed that the Mrk501, Mrk421, and 1ES 1959+650 blazars can be used to reliably detect inflation magnetic fields by the CTA observatory in the aforementioned magnetic field range of 10^{-14}–10^{-12} G in the current epoch [33].

Usually, it is roughly assumed that the average amplitude of the magnetic field is constant along the entire view line from a source to an observer. magnetic field inhomogeneities associated with the large-scale structure of the Universe, as well as inhomogeneities caused by star formation and by the activity of galactic cores, are disregarded in such a simplified approach. Lower bounds on the characteristic magnetic field strength in voids follow from the absence of secondary gamma rays from blazars. A key question of whether the cosmological magnetic field filling voids or astrophysical magnetic fields from clusters and filaments is responsible for the suppression of the secondary gamma-ray flux remains unanswered in the simplified approach. Consequently, the existing restrictions on intergalactic magnetic fields do not have sufficient foundations in this approach.

In [34], we studied the propagation of electromagnetic cascades from TeV gamma-ray sources in the constructed realistic models of the intergalactic magnetic field using the results of IllustrisTNG magnetohydrodynamic cosmological simulations. Voids in such simulations can be "polluted" by the magnetic field within the baryonic feedback model due to processes returning matter from galaxies to the intergalactic medium. We showed that astrophysical magnetic fields of clusters and filaments energy-independently suppress the secondary gamma-ray flux from most sources at a level of about 10–15%. In this case, magnetic fields $B > 10^{-12}$ G quite strongly deviate charged particles produced in secondary cascades, and the secondary gamma-ray flux is suppressed in its entire energy range. This changes the general normalization of secondary radiation but weakly affects its shape. On the contrary, the primordial magnetic field of voids ($B < 10^{-12}$ G) isotropizes the directions of only low-energy electrons and positrons, completely suppressing the corresponding part of the spectrum. This gives a signature and a method for the detection of primordial magnetic fields in voids except for a special case where a primordial gamma-ray source has a hard intrinsic spectrum with a maximum at an energy above 50 TeV. If such a source is located inside a large galaxy cluster, a magnetic field bubble formed around the cluster can suppress the cascade signal down to 50% [34].

Gamma rays from the 1ES 0229+200 blazar with a hard spectrum were analyzed in [43] in order to seek the cascade signal to obtain most model independent bounds on the intergalactic magnetic field. The analysis involved the last MAGIC observations during five years and the earlier data from the H.E.S.S. and VERITAS telescopes. Data from the Fermi/LAT observatory during 12 years were additionally used. As a result, the evolution of the source brightness in the GeV–TeV range during 15 years was established. We found that the flux from the source at energies above 200 GeV oscillates around its mean value in 14-yr observation interval. On the contrary, no indications of the flux variation were detected in the energy range of 1–100 GeV available for the Fermi/LAT observatory. Further, we simulated the cascade signal with the CRbeam and CRPropa Monte Carlo codes in order to predict the intensity of secondary gamma rays from the source from its variability in the TeV range for various values of the strength and correlation length of the magnetic field. Since the source variability in the range of 1–100 GeV due to secondary gamma rays was not detected, a lower bound $B > 1.8 \times 10^{-17}$ G is imposed on magnetic fields with a large correlation length that appear in inflation models, and a lower bound $B > 10^{-14}$ G is imposed on cosmological magnetic fields whose correlation length cannot be larger than the cosmological horizon in the corresponding epoch, e.g., those appearing in phase transitions, see Fig. 5 in [43] and references therein to various models of the origin of magnetic fields. Although this bound is weaker than that previously obtained from the analysis of the Fermi/LAT data [42], our bound is more reliable because it is based on a conservative estimate of the intrinsic spectrum of the source and includes details of the variability of its brightness in the GeV–TeV range.

The propagation of ultrahigh-energy cosmic rays in stochastic intergalactic magnetic fields with a Kolmogorov spectrum was studied in [44]. The three-dimensional picture of deviations of protons propagating in a divergent beam from the source was considered for the first time. A new phenomenon was discovered: the distribution of ultrahigh-energy cosmic rays emitted even isotropically from the source at a distance of about the Larmor radius is significantly anisotropic. The isotropic distribution is recovered again at a distance of about ten Larmor radii. Such a behavior arises in the intermediate regime between kinematic propagation in a uniform magnetic field and diffusion at distances much larger than the correlation length. The anisotropic distribution of particles on a sphere appearing in this new regime forms a filament caustic structure. The angular scale of these regions depends on the parameters and structure of the magnetic field in a radius of several correlation lengths around the source.

An image of the source from the point of view of an observer in the filament structure was studied in [45], which continued work [44]. For this, the CRbeam software package was refined by adding both the possibility of a launching a jet with a given angle and a given direction and the observer with given parameters. The observer beyond the filament structure will observe the attenuation of the flux by more than two orders of magnitude according to preliminary results. At the same time, the observer in the filament or filament fiber observes the increase in the flux of ultrahigh-energy cosmic rays by one or two orders of magnitude. Moreover, depending on his position in the filament structure, the observer sees a distorted source (elongated in the direction perpendicular to the filament) shifted from the actual direction. The dependence of the observed image of the source on the energy spectrum of particles. It was shown that features of the angular distribution of hot spot types observed in the CTA telescope can be naturally due to the propagation in intergalactic magnetic fields.

3. THEORETICAL RESULTS

3.1. Propagation of Gravitational Waves

A general equation describing the propagation of gravitational waves was derived in [46] in an arbitrary metric and with a nonzero background energy–momentum tensor including first-order perturbative corrections. This general equation is a foundation for solving numerous problems and allows some qualitative conclusions even at their formulation. In particular, the breaking of the axial symmetry of a problem due to the presence of a separated axis in addition to the propagation direction of gravitational waves results in the mixing of metric perturbation modes.

We also note that, although the propagation of metric perturbations against spaces that are not conformal plane and with nontrivial corrections to the energy–momentum tensor was considered in some works (see, e.g., [47, 48]), the equation of motion in the general case of the background space and the background energy–momentum tensor with corrections have not yet been reported and, correspondingly, analyzed by other authors. Meanwhile, problems on metric perturbations can be classified into two types: the problems with isotropic and anisotropic background spaces. In the latter case, metric perturbations cannot be decomposed into independent modes. For this reason, the mixing of modes of metric perturbations is not at focus, e.g., in works [49, 50], where metric perturbations on the Bianchi background space were considered. Our work expands the circle of problems on the propagation and evolution of gravitational waves and perturbations of the metric as a whole. It implies the possibility of considering problems where, e.g., gravitational waves pass from isotropic spatial regions to a region with local anisotropy caused by the presence of massive astrophysical objects. Thus, a gravitational wave passed through the region with anisotropy can be damped or enhanced. The generated scalar mode of metric perturbations can be possibly important in problems of cosmology and astrophysics such as the propagation of the gravitational wave near the charged rotating black hole or the magnetar and numerous other problems.

Using the results obtained in [46], we derived in [51] a system of equations for the conversion of gravitational waves to electromagnetic waves under the action of the magnetic field against the background of an arbitrary curved spacetime. The aim of that work was to estimate the influence of conversion induced by the cosmological magnetic field on the amplitude of long-wavelength relic gravitational waves. To obtain an upper bound, we rewrote this system of equations for the case of the Friedmann–Lemaître–Robertson–Walker metric and introduced some simplifying approximations: the uniformity of the background magnetic field, the smallness of gravity from the cosmological magnetic field compared to gravity of background matter, the temperature independence of the coefficient in the effective Heisenberg–Euler action, and the orthogonality of the wave vector of gravitational waves to the magnetic field vector. The interaction of produced photons with the primordial plasma was also taken into account.

The resulting system of equations was separated into two independent subsystems for two polarizations of the initial gravitational wave. The first subsystem was solved numerically for the radiation dominant epoch with the current magnetic field strength $B_0 =$ 1 nG (we recall that the magnetic field strength increases back in time as the inverse square of the scaling factor) for the frequencies 10^{-18}–10^{-16} Hz of relic gravitational waves. According to the solution, that the amplitudes of gravitational waves at these frequencies at the end of the radiation dominant epoch were suppressed by about 0.01%. It was concluded that the conversion of relic gravitational waves to electromagnetic waves under the action of the cosmological magnetic field insignificantly affects the amplitude of long-wavelength relic gravitational waves. The second subsystem of equations, which describes the conversion of the tensor mode of metric perturbations not only to electromagnetic waves but also to the scalar mode of metric perturbations will be solved in future.

3.2. Production of Superheavy Dark Matter Particles and High-Energy Cosmic Rays

The production probability of superheavy dark matter particles with masses close to the scalaron mass $M_R \simeq 3\times10^{13}$ GeV and the interaction force typical of supersymmetry was calculated in [52], where it was shown that the annihilation of these particles in clusters of dark matter can make an observable contribution to the ultrahigh-energy cosmic ray flux. Annihilation in a gravitationally bound pair of these superheavy particles is another efficient source of ultrahigh-energy cosmic rays. It was concluded that superheavy supersymmetric particles in R^2 theory are realistic candidates for dark matter carriers. Their decays or annihilation will contribute to the ultrahigh-energy cosmic ray flux at $E > 10^{20}$ eV. The absence of this contribution provides bounds on the parameters of models of heavy dark matter [53].

3.3. Massive Photons and the Electrical Asymmetry of the Universe

According to current data, if the photon mass is nonzero, it cannot exceed 10^{-18} eV [54]. At the same time, even an extremely small photon mass can have significant astrophysical manifestations. As shown in [55–57], an arbitrarily small photon mass leads to the complete disappearance of the Coulomb field of charged black holes. The disappearance rate of the Coulomb field generated by a black hole absorbing charged particles from the interstellar space in the case of the nonzero photon mass was calculated in [58]. It was shown that this rate is independent of the photon mass and, thereby, a continuous limiting transition from massive electrodynamics to Maxwell's electrodynamics is absent. In early works, it was accepted that this time is inversely proportional to the photon mass or to its square. At the existing upper bound on the photon mass, the field disappearance time would exceed the age of the Universe. Our result shows that the traceless disappearance of a charge in a black hole can lead to the charge asymmetry of the Universe in a cosmologically short time and to potentially observable effects.

As known, a higher mobility of protons compared to electrons in the interstellar gas in the current Universe results in a nonzero charge of celestial bodies [59–61]. Black holes are not exclusions and also acquire the electric charge. As a result, an equilibrium situation where the Coulomb repulsion between protons compensates their higher mobility and the electric charge reaches a certain equilibrium value occur in the canonical case. For quite light black holes with masses $M \lesssim 10^{20}$ g, the Coulomb field at the horizon becomes comparable with the Schwinger field, which leads to the production of e^+e^- pairs. Electrons are captured by the black hole, whereas positrons are emitted outside. In other words, black holes acquire a certain equilibrium charge and "convert" protons to positrons. Due to this mechanism, the black hole with a mass of 10^{20} g can acquire a positive charge exceeding 5×10^7 of elementary charges. This mechanism can partially explain the appearance of the observed 511-keV line [62, 63].

The situation is fundamentally different if the photon mass is nonzero. As mentioned above, the electric field of the black hole disappears traceless in this case. Since black holes capture more protons than electrons, the electric asymmetry of the Universe, i.e., a nonzero average spatially distributed electric charge, appears. It is noteworthy that current bounds on the charge asymmetry of the Universe are at a level of 10^{-26} elementary charge per baryon [64]. If, e.g., observations of the scattering of charged particles (protons or electrons) on the black hole show that the electric charge of a certain black hole is nonzero, it could be concluded that the photon mass is identically zero.

Large-scale though weak electric fields appearing in the charged Universe can noticeably affect the spectrum and angular distribution of cosmic rays, particularly at low energies.

The possible appearance of a nonzero average cosmological charge density would lead to accelerated cosmological expansion similar to that appearing in $F(R)$ theories, which were proposed in order to phenomenologically describe dark energy initiating the observed accelerated expansion of the Universe. However, the contribution of the electric charge of the Universe to the accelerated cosmological expansion has not yet been quantitatively considered.

It is usually assumed that the Universe is electrically neutral but this is no more than a hypothesis, in particular, because of the assumed absence of any mechanism of the charge asymmetry of the Universe. Our approach allows a noncontradictory description of the formation of the charged Universe. As well known, there are almost no absolutely valid physical statements. All statements should be verified for agreement with existing experimental data and for the absence of contradictions of any model to the established fundamental properties of the theory. Our mechanism satisfies all these requirements.

3.4. Black Holes and Baryon Asymmetry

A new mechanism of generating the baryon asymmetry of the Universe due to the asymmetric capture of baryons and antibaryons by primordial black holes was proposed in [65]. This mechanism is efficient in thermal equilibrium and at the conservation of the baryon number in particle physics, thus being an example of outgoing beyond the canonical baryogenesis scenario by A.D. Sakharov [66]. The implementation of this mechanism in the early Universe requires the existence of both supermassive baryons X with masses of about 10^{13} GeV, whose captures generate asymmetry, and other supermassive baryons Y, which results in C- and CP-symmetry breaking in radiative corrections to the scattering cross section necessary for the appearance of different mobilities of particles X and $\bar{X}$ (anti-X) in the gravitational field of the black hole in the early Universe. The lifetime of these particles should be so large that they presented in a significant number in the primordial plasma before the evaporation of primordial black holes. Furthermore, for the same reason, they should not be noticeably burned through the Zeldovich mechanism [67, 68] and their density should be much higher than the equilibrium value. This requires a small cross section for their annihilation and a long lifetime. It was shown in [65] that the proposed mechanism is efficient at larger masses of baryons and, correspondingly, smaller masses of primordial black holes. The generated asymmetry at masses of heavy baryons about 10^{13} GeV and masses of primordial black holes about 10^4 g is estimated at about the observed baryon asymmetry of the Universe. At a sufficiently late decay of these heavy baryons, the products of their decays can contribute to ultrahigh-energy cosmic ray fluxes. Thus, the proposed mechanism can in principle be verified by the contribution from high-energy particles from decays of X or annihilation of X and $\bar{X}$ to cosmic rays.

3.5. Electrodynamics of Black Holes

The study of possible mechanisms of electromagnetic emission at the merger of black holes indicates that the electric charge of the black hole in the primordial plasma appears through the Shvartsman mechanism [59], which is due to the difference between the mobilities of electrons and protons in the interstellar medium, naturally leading to the generation of accompanying radiation the process of merger of two charged bodies. A hypothetical possibility of the appearance of a nonzero charge density in the interstellar gas around the binary black holes was also considered. It was shown that the process of merger results in dipole electromagnetic radiation with the intensity depending on the acquired charge of each of the black holes and on the history of their evolution. This process can be enhanced at any nonzero photon mass because the electric asymmetry of the Universe arises at any its magnitude. In the last case, we base on the results obtained in our work [58].

3.6. Mass Spectrum of Primordial Black Holes

The chirp-mass distributions of binary black holes, which are sources of gravitational radiation detected by the LIGO/Virgo interferometers were calculated in [69, 70], where they are compared to the distribution obtained under the assumption of the lognormal mass spectrum of primordial black holes (1). The results demonstrate excellent agreement of observations with theoretical predictions, and the best fit is reached with the parameters $M_0 \approx 17M_\odot$ and $\gamma = 0.9$. Since the mass dependence is logarithmic, the distribution function quite weakly depends on M_0. In particular, the densities of black holes at $\gamma = 1$ and $M = 50M_\odot$ differ from those at $M_0 = 10M_\odot$ and $M_0 = 17M_\odot$ by a factor of 4.

A new analysis of the LIGO/Virgo/KAGRA data was given later in [71]. According to this analysis, the chirp-mass distribution of binary black holes has two pronounced peaks, which can be attributed to two different populations of binary black holes. The peak at a small mass $M_0 \sim 10M_\odot$ is due to astrophysical binary black holes formed in the local Universe at the evolution of binary stars. Their formation can be explained within the model of the collapsing core of massive stars. The second peak is due to primordial binary black holes with the lognormal spectrum with the parameters $M_0 \simeq 33M_\odot$ and $\gamma \simeq 10$. The model involves two approximately identical populations of merging astrophysical and primordial black holes.

However, the second peak with the found parameters of the initial mass spectrum is described by an almost delta distribution around $M = 33M_{\odot}$, so that neither lighter no heavier primordial black holes can be formed. The expected significant increase in the number of mergers of binary black holes in the continuing series of O4 LIGO/Virgo/KAGRA observations should clarify the possibility of describing the observed sources by a single lognormal mass spectrum of black holes.

3.7. Antimatter in Our Galaxy

One of the consequences of a mechanism for the production of black holes proposed in [3, 4] is the existence of a noticeable amount of antimatter in our Galaxy. In this context, we developed a new method to identify antimatter by narrow X-ray lines and established the relation of their intensity to the assumed density of primordial black holes [72]. Recent astronomical observations convincingly confirm this prediction, indicating a noticeable amount of antimatter in the Milky Way (see, e.g., recent review [73] and references therein). These observations are as follows.

(i) Alpha magnetic spectrometer data placed on the International Space Station indicate an excess flux of antideuterons and anti-alpha particles compared to the expected fluxes from secondary processes in cosmic rays.

(ii) The observed 511-keV annihilation line indicates a large population of positrons in the Galaxy center.

(iii) Excess gamma rays with an energy of about 500 MeV observed from 14 stars are most naturally explained by the antimatter composition of these stars [74].

All these observations are in agreement with longtime predictions of the existence of antimatter in the Galaxy [3, 4]. The fraction of antimatter is model dependent and cannot be predicted theoretically. However, the existence of a noticeable amount of antimatter in the Galaxy strongly indicates the validity of the model. It is reasonable to believe that this fraction is small. In particular, the number of antistars and their mass spectrum depend on the relative orientation of planar directions in the baryon scalar potential in the Affleck–Dine model and is most likely much smaller than the fraction of black holes with close masses. It is not stated that the mass spectrum of antistars is lognormal. The hypothesis of antimatter in the Galaxy cannot be considered as finally proven but there are serious indications to it.

4. CONCLUSIONS

To summarize, it has been shown that the multimessenger approach in both cosmological observations and theoretical problems is very productive and its development will significantly promote the further progress in this very promising field combining cosmology, quantum field theory, and particle physics.

The main results obtained in the reviewed works are as follows.

(i) Realistic maps of intergalactic magnetic fields have been plotted, bounds on their strengths have been obtained from γ-astronomy data, and the possibility of improving these bounds has been examined.

(ii) The contribution from superheavy dark matter particles to the spectrum of ultrahigh-energy cosmic rays with $E > 10^{20}$ eV, which cannot be explained by conventional astrophysical sources, has been estimated and this estimate can be used to experimentally verify the model.

(iii) A hypothetical model of the charged Universe has been proposed.

(iv) A new mechanism of generating the baryon asymmetry of the Universe by primordial black holes has been developed.

(v) Electromagnetic processes at the merger of black holes have been studied.

(vi) The mass spectrum of primordial black holes has been verified in chirp masses measured by the LIGO/Virgo/KAGRA interferometers and in the observed number of supermassive and intermediate-mass black holes and very good agreement of this mass with observations has been achieved, see [70].

(vii) The remarkable prediction of a significant amount of antimatter in the Milky Way has been supported by observations of positrons, antinuclei, and antistars.

(viii) A new method has been developed to identify antistars in the Galaxy.

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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