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ELEMENTARY PARTICLES AND FIELDS
Theory

Cosmic Rays as an Additional Source of Information about Nonequilibrium Processes in the Universe

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Abstract—It is shown that cosmic rays may serve as a source of information about nonequilibrium processes in the universe (evaporation of primordial black holes, annihilation of domains of antimatter, decays of metastable particles, etc.) over a long period of cosmological evolution beginning from $t \sim 10^{12}$ s until the present time. Such processes are associated with the hypothetical physics of phenomena that occur in the very early universe as predicted by modern unified field theories.

The majority of modern unified field theories invoke new, fundamental, symmetries that lead to the prediction of various types of supermassive particles and fields. At present, the physics of such objects is beyond reach under laboratory conditions [1–3]. Attempts at verifying these predictions are therefore based on indirect methods for studying manifestations of these new fields and particles.

Natural conditions for the occurrence of ultrahigh-energy processes associated with new physics are realized in the very early universe. For this reason, the study of cosmological implications of unified field theories is a logical step in the development of modern elementary-particle physics and cosmology [4–6].

Hypothetical processes, which began to proceed in the very early universe, can become, at later stages of its evolution, sources of particles whose energies considerably exceed the mean heat energy of cosmological plasma. Among such sources, we would like to mention the evaporation of primordial black holes (PBH), the decays of metastable particles, and the annihilation of domains of antimatter [7–9].

There exist various theories describing the origins of cosmic rays that are associated with the activity of galaxy cores, with supernova bursts, with processes in the magnetospheres of pulsars, and with various mechanisms of acceleration of charged particles [10]. All these theories imply that cosmic rays arise following the instant $t \sim 10^{16}$ s, at which the formation of modern galaxies began. If we assume that cosmic rays (a part of their spectra) are due to the presence of hypothetical sources of nonequilibrium particles in the early universe, data on cosmic rays furnish information about such sources over a long period of cosmological evolution beginning from $t \sim 10^{12}$ s until now.

On the whole, the problems of cosmoarcheology (which is aimed at setting constraints on the parameters of hypothetical fields and particles by analyzing the possible effects of these objects in the observed fluxes of cosmic rays) require studying logical connections between the cosmological implications of specific elementary-particle theories and the parameters of hypothetical sources of elementary particles in the universe and call for examining the effect of processes that occur in the galaxy on the expected fluxes of cosmic rays from these sources. Finally, a comparative analysis of all possible sources of observed cosmic rays is necessary for isolating the admissible contribution of hypothetical sources.

For a first approximation, we disregard here physical processes in the galaxy and study the possibility for the various components of cosmic rays to serve as a source of some information about nonequilibrium processes in the early universe. This possibility, should it be realized, will form the basis for the ensuing cosmoarcheological analysis relating the problem of hypothetical particles and fields in the universe to the experimental physics of cosmic rays.

Let us consider the model of a hot universe with the current value $H = 75$ km/s Mpc of the Hubble constant, the baryon density of $\rho_B = 5 \times 10^{-31}$ g/cm^3, and the total cosmological density determined by the dominant contribution of the hidden mass $\Omega = 1$. According to the general kinetic approach to nonequilibrium processes in the universe [11], interaction of particles with cosmological plasma is insignificant for $H\tau_i \geq 1$ $(1/n\sigma v \geq t)$, where τ_i is the characteristic time during which particles of the ith type undergo interaction with cosmological plasma, and t is cosmological time. In this region, the universe is therefore transparent to nonequilibrium particles, so that their spectrum is affected only by the cosmological redshift. In the majority of cases, the fluxes of nonequilibrium particles from hypothetical sources can contain particles of various types (photons, e^+e^- pairs, $\bar{p}p$ pairs, $\bar{n}n$ pairs, etc.). The energy and time intervals in which the universe is transparent to nonequilibrium particles of each specific type are determined by the main processes of interaction between such particles and cosmological plasma. We consider in

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detail nonequilibrium (anti)protons, photons, electrons, and positrons.

Nonequilibrium (anti)protons. Nuclear (elastic and inelastic) scattering on hydrogen and ^{4}He nuclei, the main products of cosmological nucleosynthesis, is the main process of interaction between high-energy (anti)protons and cosmological plasma [12]. For estimates, we take the values $\sigma_{nucl} \sim 10^{-26}$ cm^2, $n_\gamma \simeq 5 \times 10^{31} t^{-3/2}$ cm^{-3} [12], and $n_B/n_\gamma \sim 10^{-9}$. Setting $v \approx c$ for high-energy particles and proceeding from the criterion $1/n_B\sigma_{nucl}c > t$, we obtain $t > 2 \times 10^{14}$ s; that is, at the radiation-dominated (RD) stage, the rate of nuclear processes for nonequilibrium (anti)protons in cosmological plasma is much greater than the rate of cosmological expansion (the completion of the RD stage corresponds to the instant $t \sim 10^{11}$ s). At the matter-dominated (MD) stage, we have $n_\gamma \simeq 3.6 \times 10^{37}/t^2$ cm^{-3}, which corresponds to a current relic-radiation (RR) temperature of 2.7 K. It follows that the baryon concentration is

$$n_B = \frac{n_B}{n_\gamma} n_\gamma \approx \frac{3.6 \times 10^{29}}{t^2} \text{ cm}^{-3}.$$

Hence, for $t > 1/n_B\sigma_{nucl}c \sim 5 \times 10^{13}$ s, the universe is transparent to high-energy (anti)protons of virtually arbitrary energy. From this instant on, nonequilibrium fluxes of (anti)protons from hypothetical sources may contribute to the spectrum of cosmic rays observed at present.

Nonequilibrium photons. Compton scattering on electrons, the production of electron–positron pairs, and the scattering of a nonequilibrium photon by a relic photon [$\gamma(E) + \gamma(\mathrm{RR}) \longrightarrow \gamma(E) + \gamma(E)$] are the main processes of interaction between nonequilibrium photons and cosmological plasma. In the formulas presented below, the energies, time, and cross sections are given in GeV, seconds, and cm^2, respectively [13].

(a) Compton scattering.

For low energies [$E \le m_e/2$, $x = (s_{\gamma e} - m_e^2)/m_e^2 = 2E/m_e \le 1$), the cross section for this process is

$$\sigma_{\gamma e} = (8\pi r_e^2)/3 = 6.7 \times 10^{-25} \text{ cm}^2,$$

For high energies ($E \ge m_e/2$, $x \ge 1$), we have

$$\sigma_{\gamma e} = \frac{\pi r_e^2 m}{E}\left(\ln\left(\frac{2E}{m}\right) + \frac{1}{2}\right)$$

$$= 1.3 \times 10^{-28} \frac{\ln(3.9 \times 10^3 E + 1/2)}{E} \text{ cm}^2.$$

Considering that $n_\gamma = 3.6 \times 10^{37}/t^2$ cm^{-3} at the MD stage and that $n_\gamma = 5 \times 10^{31} t^{-3/2}$ cm^{-3} at the RD stage, we use the condition $1/n_\gamma\sigma_{\gamma e}c < t$, under which the universe is transparent, to obtain the admissible t values. The results are follows:

	RD	MD	
$E \le m_e/2$	$t > 10^{18}$ s	$t > 7.2 \times 10^{14}$ s	(1)
$E \ge m_e/2$	$t > (3.8 \times 10^{10} \ln(3.9 \times 10^3 E)^2)/E^2$	$t > (1.4 \times 10^{11} \ln(3.9 \times 10^3 E))/E$	

(b) Production of electron–positron pairs.

The energy threshold for pair production in collisions between high-energy photons of energy E and relic photons that are in thermal equilibrium at temperature T depends on the cosmological time through the dependence of T on t (we have $T(\mathrm{GeV}) = 1.3 \times 10^{-3}/\sqrt{t(c)}$ at the RD stage and $T(\mathrm{GeV}) = 0.1/(t(c))^{2/3}$ at MD stage):

	RD	MD
$s_{\gamma\gamma} = 4ET = m_e^2$	$E = 4.7 \times 10^{-5}\sqrt{t}$	$E = 6.5 \times 10^{-7} t^{2/3}$.

(2)

The cross section for the production of an electron–positron pair can be estimated as

$$\sigma_{\gamma\gamma \to e^+e^-} = \frac{\pi r_e^2}{2}(1 - v^2)\left\{(3 - v^4)\ln\left(\frac{1+v}{1-v}\right) - 2v(2 - v^2)\right\} \simeq \frac{\pi r_e^2}{2\sqrt{(ET/m_e^2) - 1}},$$

where $v = \sqrt{1 - (m_e^2/ET)}$. Comparing $\tau_{\gamma\gamma \to e^+e^-} = 1/n_\gamma\sigma_{\gamma\gamma \to e^+e^-}c$ and $1/H$, we find that, for nonequilibrium-photon energies exceeding the threshold of pair production ($E > m_e^2/4T$), the rate of the pair-production process is greater than the rate of expansion of the universe; hence, a nonequilibrium photon with $E > m_e^2/4T$ is decelerated in cosmological plasma, losing energy by the production of electron–positron pairs. For nonequilibrium-photon energies $E < m_e^2/4T$, pair production is impossible; in this region, the principal processes are Compton and photon–photon scattering.

(c) Scattering of a nonequilibrium photon by relic radiation.

Photon–photon scattering is described as a two-stage process in which the production of a virtual electron–positron pair by two initial photons is followed by the annihilation of this pair into final photons. For an estimate, we assume that the relation $s_{\gamma\gamma} = (P_{\gamma(E)} + P_{RR})^2 \simeq 4ET$ holds for a collision between a nonequilibrium photon of energy E and a relic photon. In the energy region $E < m_e^2/4T$ ($s_{\gamma\gamma} < m_e^2$), the cross section for this process is given by

$$\sigma_{\gamma\gamma\to\gamma\gamma} = 0.031\alpha^2 r_e^2(\sqrt{s_{\gamma\gamma}}/m_e^2)^6 = 4.7\times10^{-10}E^3T^3\ \mathrm{cm}^2.$$

For $E > m_e^2/4T$ ($s_{\gamma\gamma} > m_e^2$), we have

$$\sigma_{\gamma\gamma\to\gamma\gamma} = 4.7\alpha^4(\hbar^2/s_{\gamma\gamma}) = (1.3\times10^{-26})/ET\ \mathrm{cm}^2.$$

Taking into account the dependence $T(t)$ at the RD and MD stages and using the criterion $1/n_\gamma\sigma_{\gamma\gamma\to\gamma\gamma}c > t$, we find that the admissible values of E are as follows:

	RD	MD
$E < m_e^2/4T$	$E < 8.7\times10^{-9}t^{2/3}$	$E < 1.3\times10^{-12}t$
$E > m_e^2/4T$	$E > 1.5\times10^9$	$E > (1.4\times10^{13})/t^{1/3}$

Thus, at the MD stage, there is an interval in which the universe is transparent to photons. For $E_\gamma < 1$ GeV, Compton scattering on electrons plays the dominant role in the interactions of a nonequilibrium photon with cosmological plasma. From (1), it can be seen that, for $E_\gamma < m_e/2$, the universe becomes transparent beginning from the instant 7×10^{14} s. In the energy range $m_e/2 < E_\gamma < 1$ GeV, the universe is transparent, provided that

$$E_\gamma/\ln(3.9\times10^3E_\gamma + 1/2) > (1.4\times10^{11})/t.$$

For estimates, we can assume that

$$E_\gamma > (1.4\times10^{12})/t. \tag{3}$$

At higher energies (1 GeV $< E_\gamma < 10^5$ GeV), the production of electron–positron pairs ($\gamma\gamma \longrightarrow e^+e^-$) and the scattering of a nonequilibrium photon by relic radiation come into play. At the MD stage, the threshold for the production of electron–positron pairs is [see (1)]

$$E_\gamma < 6.5\times10^{-7}t^{2/3}. \tag{4}$$

In this energy region, the scattering of a nonequilibrium photon by relic radiation ($\gamma\gamma \longrightarrow \gamma\gamma$) leads to a somewhat more stringent energy threshold of universe transparency:

$$E_\gamma < 1.3\times10^{-12}t. \tag{5}$$

Thus, the universe becomes more transparent at $t \sim 10^{12}$ s in a narrow interval of photon energies around 1 GeV. For 10^{12} s $< t < 10^{15}$ s, this interval is as follows:

$$(1.4\times10^{12})/t < E_\gamma < 1.3\times10^{-12}t. \tag{6}$$

In terms of the redshift, it can be represented as

$$4\times10^{-6}(1+z)^{3/2} < E_\gamma < (4\times10^5)/(1+z)^{3/2}. \tag{7}$$

Because of the redshift effect, this interval has transformed by now to become

$$4\times10^{-6}(1+z)^{1/2} < E_\gamma^{\mathrm{obs}} < (4\times10^5)/(1+z)^{5/2}. \tag{8}$$

For $t > 7\times10^{14}$ s, the transparency interval in energy is bounded only from above [the right-hand inequalities in (6)–(8)]:

$$E_\gamma < 1.3\times10^{-12}t,\quad E_\gamma < (4\times10^5)/(1+z)^{3/2},\quad E_\gamma^{\mathrm{obs}} < (4\times10^5)/(1+z)^{5/2}. \tag{9}$$

The results obtained for photons are in accord with the investigations reported by Zdziarski and Svensson [14], who treated the absorption of γ rays interacting with relic radiation and baryon matter in terms of the optical thickness and redshifts.

Nonequilibrium electrons and positrons. Scattering on relic radiation (inverse Compton effect) is the main process of interaction between nonequilibrium electrons (and positrons) and cosmological plasma. Considering that $n_e/n_\gamma \sim 10^{-9}$ and using the estimates obtained above for nonequilibrium photons, we can see that, at present, the universe is opaque to nonequilibrium electrons and positrons. Direct fluxes of electrons and positrons from cosmological sources can be observed in the modern universe (as an isotropic background) only if their source is effective at present.

Thus, data on the (anti)proton component of cosmic rays can be used to deduce information about nonequilibrium processes proceeding in the universe after the instant 5×10^{13} s ($z = 330$). The photon component of cosmic rays carries information about nonequilibrium processes in the interval

$$4\times10^{-6}(1+z_*)^{1/2} < E < (4\times10^5)/(1+z_*)^{5/2}$$

provided that these processes occur for $z < z_*$ ($60 < z_* < 4500$); if $z_* < 60$, the interval is bounded only from above:

$$E_\gamma < (4\times10^5)/(1+z_*)^{5/2}.$$

The regions in which the universe is cosmologically transparent to photons and (anti)protons are illustrated in the figure.

Depending on the initial mass, evaporating PBHs can be sources of all nonequilibrium particles listed above. Analysis of effects associated with the evaporation of PBHs and the resulting constraints on the mass spectrum of PBHs make it possible to obtain information about the cosmology of the very early universe and about the processes that occur in it [6–9]. The full time of PBH evaporation depends on the initial PBH mass as $t \approx 10^{-27}M_0^3$. Primordial black holes with masses not less than $M \sim 10^{10}$ g give rise to reactions of nonequilibrium nucleosynthesis and distort the RR spectrum.

Let us dwell at some length on the effects that evaporating PBHs can exert on the photon component of cosmic rays.

(*i*) If the time of PBH evaporation exceeds the age of the universe ($M > 10^{15}$ g)—at present, such PBHs would be sources of nonequilibrium particles—the effect of an increase in the temperature of the PBH surface during radiation can be disregarded. The Planck spectrum of PBH radiation is determined by the initial PBH mass: $T = m_{Pl}^2/8\pi M$. The radiation maximum $E_{max} \approx 3T$ for such PBHs does not exceed 0.03 GeV. If they indeed exist in the universe, photons with energies $E_\gamma > 0.03$ GeV must correspond to the exponential part of blackbody radiation. Since the instant z_* (at which the universe becomes transparent for a definite energy interval), the effects of the cosmological redshift for quanta studied above can be taken into account in the normalization of the total energy release:

$$Q_* = \int \frac{d\varepsilon}{dt}dt = \int_{z_*}^{0} \frac{\sigma T^4}{(1+z)^4}\left(-\frac{3}{2}\right) 3 \times 10^{17} \frac{d(1+z)}{(1+z)^{5/2}}$$

$$\simeq \frac{1}{5} Q \left(1 - \frac{1}{(1+z_*)^{15/2}}\right).$$

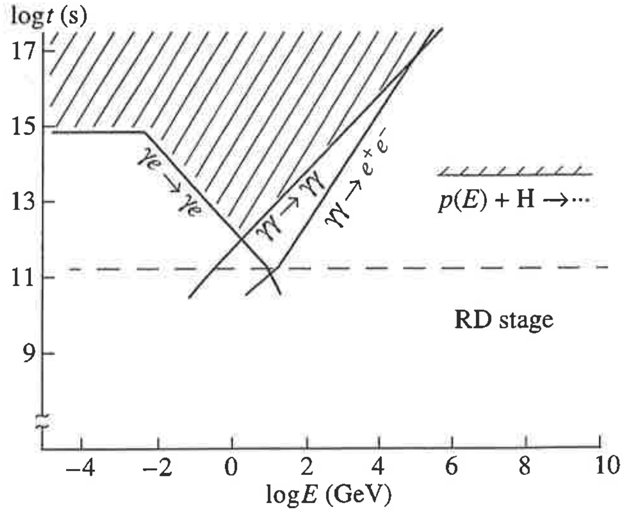
(*ii*) Primordial black holes with masses $M < 10^{13}$ g do not affect the spectrum of cosmic rays: they evaporate prior to the instant 10^{12} s, at which the universe becomes transparent to photons with energies in the region around 1 GeV. Primordial black holes with 10^{13} g $< M < 10^{15}$ g evaporate in the interval between 10^{12} and 10^{18} s. They affect the photon component of cosmic rays in a certain energy range. At the latest stages of evaporation, the PBH temperature increases to the Planck scale T_{Pl}, so that the total photon spectrum observed at present is formed [in contrast to case (*i*) for energies in excess of 0.03 GeV)] primarily by the Rayleigh–Jeans components of the blackbody spectra of PBH radiation:

$$\int u(E, T) S dE dt = \int k \frac{E^3}{e^{E/T} - 1} S dE dt$$

$$= \frac{k}{4\pi} \int \frac{E^3 dE dt}{(e^{E/T} - 1) T^2} = \frac{3 \times 10^{12} k}{4\pi} \int \frac{E^3 dE dT}{T^6 (e^{E/T} - 1)},$$

$$\int u(E, T) S dE dt = \begin{cases} \dfrac{10^{12} \times k}{8\pi} E^2 \dfrac{dE}{T_0^6}, & E < \dfrac{T_0}{1+z_*} \\[2ex] \dfrac{10^{12} \times k dE}{8\pi \; E^4}, & \dfrac{T_0}{1+z_*} < E < T_{Pl}. \end{cases}$$

Here, T_0 is the initial PBH temperature and S is the PBH surface area. A considerable part of PBH energy is concentrated in cosmic rays and depends on the initial PBH temperature.



Regions of cosmological transparency of the universe.

All the above applies to (anti)proton fluxes from PBHs as well. For them, the universe becomes transparent at $t \simeq 5 \times 10^{13}$ s. Primordial black holes with masses $M < 4 \times 10^{13}$ g do not affect the (anti)nucleon component of cosmic rays.

Thus, data on cosmic rays can furnish information about nonequilibrium processes in the universe, provided that these processes occur after the instant $t \sim 10^{12}$ s. Of special interest are the region $E_\gamma < 10^4$ GeV for the photon component of cosmic rays and the entire interval of accessible energies of cosmic (anti)protons.

The subsequent cosmoarcheological analysis will be aimed at relating the admissible parameters of hypothetical sources of nonequilibrium particles to the expected fluxes of antiprotons that can be detected in planned cosmic experiments GILDA [15] and WIZARD-SAT [16].

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