the Larmor circles under the action of a 'seed' signal, and then the bunches impart their rotational energy to the wave. The effectiveness of these processes may be so high that modern gyrotrons range up to 50% in efficiency.

For the electrodynamic systems in gyrotrons, selective resonators in the form of sections of weakly irregular cylindrical waveguides are typically used (see Fig. 5), with the highest-Q oscillations being those with one longitudinal variation and with the frequencies closest to the cut-off waveguide frequencies. These modes correspond to the least values of the longitudinal wavenumber and the Doppler correction to the frequency, and are therefore least sensitive to electron velocity spread. To provide the optimal value of the force acting on the particles, as well as to reduce the risk of a high-frequency breakdown at the walls and decrease their heating, high-power gyrotrons involve resonators that are many times greater in diameter than the working wavelength and working modes with a complex transverse structure. It is remarkable that using the resonance in a magnetic field with a high degree of uniformity and injecting the electron beam into the domain with a high effective mode field, it has been possible to excite these modes with only a small admixture of undesirable waves.

Gyrotrons intended for plasma heating are broadly used in controlled thermonuclear fusion facilities to provide enormous power, of the order of 1 MW, in a cw oscillation mode at frequencies 30 – 170 GHz. Furthermore, lower-power 5 – 300 GHz gyrotron oscillators and amplifiers find technological applications, as well as applications in radars, spectroscopy, and diagnostics of various media. Recently, in the prototypes of pulsed gyrotrons, it has been possible to obtain oscillation at the frequency 1 THz. Obtaining this frequency requires a hard-to-attain magnetic field, 36 T when operating at the fundamental cyclotron resonance. In recent years, efforts have been intensified to obtain generation at higher harmonics, which requires lower magnetic fields.

Reverting to the beginning, we note that the millimeter wavelength range and, to a large extent, the submillimeter range are presently mastered by electronic devices based on various principles. In accordance with Ginzburg's predictions [1], the role of devices that rely on the emission of electron oscillators is great in these ranges. True, the stimulated radiation of previously unphased particles resulting from their self-bunching but not the radiation of preformed electron bunches immediately considered in Ref. [1] has turned out to be most efficient. The devices based on the stimulated radiation of electron oscillators already provide coherent high-power radiation not only in the above ranges but also up to the vacuum ultraviolet range, and may allow obtaining coherent X-ray radiation in the near future. The analysis of elementary mechanisms of emission by 'free' electrons and the new ideas advanced in Ref. [1] have had an impact on the development of all high-frequency electronics.

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Cosmic accelerators for ultrahigh-energy particles

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1. Introduction

Ginzburg made a significant contribution to solving the problem of the origin of cosmic rays, in particular, by analyzing the synchrotron radiation of their constituent high-energy electrons, developing the concept of the galactic cosmic ray halo, and investigating several other problems (see his review Ref. [1] and the works of his school, e.g., Refs [2, 3]). Many questions still remain open in this area; however, as before, according to Ref. [1], "the most important problem yet to be solved in cosmic ray astrophysics is the origin of cosmic rays of ultrahigh energy." This problem is discussed in our report, which is based on previously published works [4 – 6].

The cosmic ray composition is dominated by positive-charged ions, primarily protons, while the particle distribution function over energies, $\mathrm{d}N/\mathrm{d}E$, is described with a high degree of accuracy by a power-law dependence with a break (a knee): $\mathrm{d}N/\mathrm{d}E \propto E^{-2.7}$ for energies below $\approx 3 \times 10^{15}$ eV and $\mathrm{d}N/\mathrm{d}E \propto E^{-3}$ for higher energies (see, e.g., review Ref. [7]). The properties of cosmic rays with energies up to 10^{17} eV, which have galactic origin and are produced primarily in

supernova explosions, were considered, e.g., in Ref. [3] and are not discussed below.

The question of the highest energy of cosmic rays is still unanswered. To date, particles with energies up to 10^{20} eV have been detected. Observations at higher energies encounter serious difficulties, because the expected flux is less than one particle per square kilometer per century. The sources of these particles are not known, either; however, the extragalactic origin of ultrahigh-energy cosmic rays ($\gtrsim 10^{18}$ eV) may be considered established. Two circumstances argue in favor of this conclusion. First, protons with energies above 10^{18} eV and heavy ions with energies $\gtrsim 2 \times 10^{19}$ eV are weakly deflected by the magnetic field of our galaxy, and therefore their production in galactic sources would lead to an increase in the flux in the direction towards the galactic nucleus and/or in the galactic disk plane, whereas the observed cosmic ray flux is virtually isotropic. Second, recently obtained evidence indicates that the cosmic ray spectrum steeply drops for energies higher than 5×10^{19} eV [8], which is consistent with predictions made by Kuz'min and Zatsepin [9] and Greisen [10]. The effect they point out is that protons with energies above $\gtrsim 5 \times 10^{19}$ eV rapidly (on the cosmological time scale) lose energy due to the interaction with the microwave background radiation and reach us only from distances $\lesssim 50$ Mpc. This leads to a strong decrease in the observed flux of particles with energies of the order of 10^{20} eV if they are produced primarily by distant sources.

We start from the natural hypothesis that the ultrahigh-energy cosmic rays originate in the acceleration of ions in the electromagnetic fields of astrophysical objects. An alternative hypothesis (termed 'top-down') requires invoking presently unknown physical phenomena and states that the source of cosmic rays is the decay of superheavy particles of dark matter [11]; produced in this case are the highest-energy cosmic rays, which subsequently lose their energy to form the observed distribution.

The fact that particles with energies of the order of 10^{20} eV exist in space should not come as a surprise. The cosmic plasma is far from thermodynamic equilibrium, and the effective temperature corresponding to its large-scale motions exceeds the energy of cosmic ray particles by several dozen orders of magnitude. A fraction of the ions would be expected to accelerate to very high energies due to multiple collisions with moving cosmic plasma clouds. This mechanism was advanced by Fermi [12]. With the knowledge of the lifetime of the cosmic rays in our galaxy, it is possible to calculate the required source power. It turns out to be of the same order of magnitude as the time-averaged power of supernova explosions, which are the main driving force of turbulence in the interstellar medium. This circumstance led to the hypothesis that supernova explosions are the main source of cosmic rays [13]. After the discovery of the diffusive particle acceleration at a shock front [14, 15] and the emergence of numerous detailed calculations (see, e.g., Ref. [16]), it became clear that cosmic rays emerge early in the existence of a supernova remnant, while the shock generated in its explosion remains strong. This picture was borne out experimentally (see, e.g., Ref. [17]): hard gamma-ray radiation caused by the inelastic collisions of accelerated cosmic rays with interstellar medium particles was detected from supernova remnants.

Shock waves in supernova remnants are capable of accelerating protons to an energy approximately corresponding to the knee in the cosmic ray spectrum and the nuclei of heavy elements with the charge $q = Ze$ can be accelerated to a Z-times higher energy, which ranges up to $\sim 10^{17}$ eV for iron. The further acceleration is impeded by the limited size of the remnant and the magnitude of the magnetic field in it: the high-energy ions are not confined by the magnetic field and escape from the shock. Explaining the origin of ultrahigh-energy cosmic rays requires objects of greater size or with stronger electromagnetic fields. But introducing such objects leads to problems, which may be divided into two groups.

First, these are mutually antithetic requirements on the electromagnetic fields in the objects of interest. On the one hand, they should be strong enough to allow acceleration to the required energy in a time during which the particles are confined in the accelerator. On the other hand, they should be sufficiently weak so as not to lead to excessive radiative losses. As shown in Section 2, the simultaneous fulfillment of the above requirements significantly limits the minimal size of the accelerator and dictates the minimal energy stored in its field. Second, the acceleration mechanism should be efficient enough: owing to the limited power of appropriate astrophysical objects, they should transfer a significant fraction of their power to ultrahigh-energy cosmic rays. The converter acceleration mechanism considered in Section 3, which is a Fermi-type mechanism, meets this requirement. In Section 4, we discuss several peculiarities of the energy gain and radiation for particles accelerated by this mechanism in relativistic plasma flows.

2. Minimal requirements on cosmic accelerators

The mere existence of the ion acceleration mechanism and the fulfillment of its realization conditions are not sufficient for an astrophysical object to become a source of ultrahigh-energy cosmic rays. It is also required that the acceleration power exceed the total particle energy loss rate. A large number of processes responsible for energy losses by high-energy ions may be eliminated or brought to an admissible low level by appropriate selection of the astrophysical object — the source of cosmic rays. Only the losses related to the accelerating electromagnetic field itself are fundamentally unavoidable. It is these losses that impose fundamental limitations on the parameters of cosmic accelerators.

We consider a particle acceleration region of size R. It can be naturally assumed that nothing like linear accelerators exists in space, and hence the curvature radius of magnetic and electric field lines is smaller than or of the order of R.

The accelerated particle trajectory depends on the energy loss rate. A high radiative loss rate leads to a rapid decrease in the particle momentum component transverse to the field direction and compels the particle to move along the field line. In the case of slow losses, the field geometry has only a weak effect on the particle trajectory at the angle $\sim 45°$ with the field lines.

A particle accelerates to the limiting energy defined by the smallest of two values: either the work of the accelerating force in a time during which the particle is confined in the accelerator or the energy value at which the energy loss rate $\dot{\varepsilon}_{\rm rad}$ becomes comparable with the acceleration rate. The balance of acceleration and losses is reached for

$$\dot{\varepsilon}_{\rm rad} = \frac{2}{3}\,\gamma^4\,\frac{q^2}{R^2}\,c = \eta q B c \qquad (1)$$

in the case where curvature radiation [2] prevails (assuming that the particle moves along an arc of radius R) or for

$$\dot{\varepsilon}_{\rm rad} = \frac{2}{3}\,\gamma^2 \left(\frac{q^2}{mc^2}\right)^2 c\left(B_\perp^2 + E_\perp^2\right) = \eta q B c \tag{2}$$

in the case where synchrotron or Bremsstrahlung radiation prevails. Here, γ is the Lorentz factor of the particle, m is its mass, $B_\perp$ and $E_\perp$ are the rms magnitudes of the field components perpendicular to the particle momentum, and η is the dimensionless acceleration rate, i.e., the ratio of the mean accelerating electric field $E_{\rm eff}$ to the magnetic one.

Comparing Eqns (1) and (2) shows that the curvature radiation leads to lower (and hence more favorable to acceleration) radiative losses when the particle energy $\varepsilon = \gamma mc^2$ satisfies the condition

$$\varepsilon < qR\sqrt{B_\perp^2 + E_\perp^2}\,. \tag{3}$$

There is no way of violating condition (3), because this would lead, somehow or other, to a contradiction: either the particle gyroradius $r_{\rm H} = \varepsilon/(qB_\perp)$ turns out to be formally greater than R, and therefore the particle is not confined in the accelerator and the acceleration terminates at the instant of particle escape for $\varepsilon \leqslant qRB_\perp$, or (when $B_\perp \ll E_\perp$) the particle is not confined from the very beginning, and hence the energy gain is bounded by the difference of the electric potential across the acceleration region, i.e., $\varepsilon \leqslant qRE_{\rm eff} = \eta qRB$. In what follows, we neglect a factor ~ 1 and assume that $B = B_\perp$ and $E = E_\perp = E_{\rm eff} = \eta B$.

Therefore, the absolute upper bound for the particle energy is defined by either the acceleration – losses balance condition (1),

$$\varepsilon_{\rm max}^4 = \frac{3\,\eta B R^2}{2\,q}\,(mc^2)^4\,, \tag{4}$$

or condition (3), specifically, the lesser of these two values.

The total energy of the electromagnetic field in the spherical volume of radius R for an accelerator capable of generating cosmic rays with an energy $\varepsilon_{\rm max}$ is $W = R^3(B^2 + E^2)/6$, which gives

$$W > \frac{2}{27}\,\frac{q^2}{R}\left(\frac{\varepsilon_{\rm max}}{mc^2}\right)^8 \frac{1+\eta^2}{\eta^2} \tag{5}$$

for Eqn (4) and

$$W > \frac{R}{6}\left(\frac{\varepsilon_{\rm max}}{q}\right)^2 \tag{6}$$

for condition (3).

It is possible to minimize the requirements on the field energy in the accelerator by increasing R in relation (5) and decreasing it in relation (6). This implies the existence of the optimal size

$$R^{\rm (opt)} \approx \frac{2}{3}\,\frac{\sqrt{1+\eta^2}}{\eta}\,\frac{q^2\varepsilon_{\rm max}^3}{(mc^2)^4}\,, \tag{7}$$

which corresponds to the minimal possible accelerator energy content

$$W^{\rm (opt)} \approx \frac{1}{9}\,\frac{\sqrt{1+\eta^2}}{\eta}\,\frac{\varepsilon_{\rm max}^5}{(mc^2)^4} \tag{8}$$

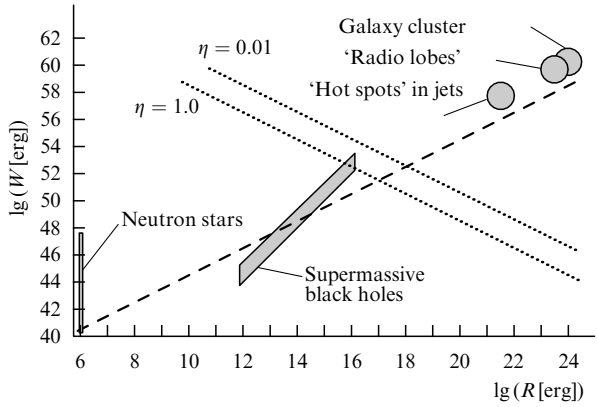

Figure 1. Minimal requirements on the energy content of a 10^{20} eV proton source for acceleration efficiencies $\eta = 1$ and $\eta = 10^{-2}$: expressions (5) (dotted lines) and (6) (dashed line) as functions of the acceleration region size.

and the optimal magnitude of the magnetic field

$$B^{\rm (opt)} \approx \frac{3}{2}\,\frac{\eta}{1+\eta^2}\,\frac{(mc^2)^4}{q^3\varepsilon_{\rm max}^2}\,, \tag{9}$$

with $E^{\rm (opt)} = \eta B^{\rm (opt)}$. The energy requirements defined by relations (5) and (6) are presented in Fig. 1. Also shown in Fig. 1 are the parameter ranges typical for neutron stars, rotating black holes with a near-Eddington accretion rate, galactic clusters, and those regions of jets in active galactic nuclei where the ejection velocities are no longer relativistic. Figure 1 shows two types of such regions: hot spots, i.e., bright objects of subkiloparsec size located at a distance ranging from several to dozens of kiloparsecs from the nucleus, and radio lobes — regions measuring several hundred kiloparsecs formed by a shock wave that delimits the jet substance and the intergalactic medium.

We estimate the optimal parameters for a source of protons with the energy $\varepsilon_{\rm max} = 10^{20}$ eV. The total energy of the electromagnetic field in the accelerator should be no less than $W^{\rm (opt)} \approx 3 \times 10^{51}$ erg, the optimal size is of the order of 10^{17} cm, and the optimal magnitude of the magnetic field is ~ 3 G. In these estimates, we assumed that $\eta = 1$ to relax the requirements on the field energy in the accelerator as much as possible. An even greater value of η (the electric field stronger than the magnetic one) does not lead to an appreciable lowering of $W^{\rm (opt)}$.

Naturally, the above results also apply to an accelerator that moves as a whole with a Lorentz factor $\Gamma \gg 1$; in this case, all quantities are measured in the comoving frame of reference. However, it is convenient to transform Eqns (7) – (9) such that $W^{\rm (opt)}$ and $\varepsilon_{\rm max}$ are measured in the laboratory frame of reference and $R^{\rm (opt)}$, $B^{\rm (opt)}$, and $E^{\rm (opt)}$ in the comoving frame of reference. We substitute $\varepsilon_{\rm max} = \Gamma\varepsilon'_{\rm max}$ to obtain

$$W_{\rm rel}^{\rm (opt)} = \frac{W^{\rm (opt)}}{\Gamma^4}\,, \tag{10}$$

$$R_{\rm rel}'^{\rm (opt)} = \frac{R^{\rm (opt)}}{\Gamma^3}\,, \tag{11}$$

$$B_{\rm rel}'^{\rm (opt)} = \Gamma^2 B^{\rm (opt)}\,, \tag{12}$$

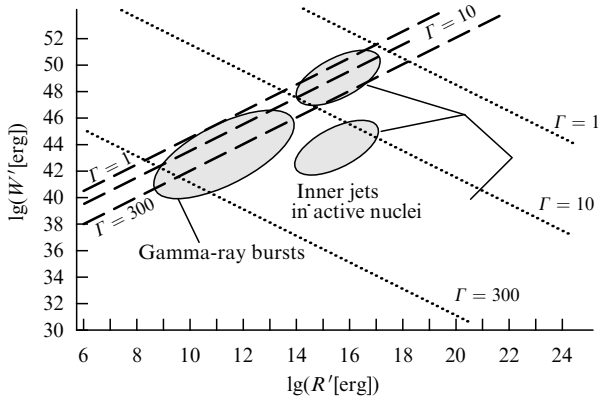

Figure 2. Minimal requirements on the energy content of a 10^{20} eV proton source as functions of the acceleration region size in the comoving frame of reference $R' = R/\gamma$. Expression (5), which scales as Γ^{-7}, is represented by dotted lines for an accelerator at rest and for Lorentz factors $\Gamma = 10$ and $\Gamma = 300$ ($\eta = 1$). Expression (6) is represented by dashed lines (scales as Γ^1). For inner jets in active galactic nuclei, the upper zone corresponds to hadronic gamma-ray radiation models and the lower zone to the leptonic ones.

where the quantities measured in the comoving frame of reference are primed.

The energy requirements represented by Eqns (10)–(12) are shown in Fig. 2. The parameter domains characteristic of the plasma flows in gamma-ray bursts ($\Gamma \sim 300$) and inner, relativistic ($\Gamma \sim 10$) jet regions in active galactic nuclei are indicated. Clearly, the acceleration of ultrahigh-energy cosmic rays in ultrarelativistic flows has the advantage of bringing the optimal size to a more 'comfortable' range, which is especially important for short-lived sources, for instance, gamma-ray bursts.

3. Converter acceleration mechanism

The most universal supplier of high-energy particles is the Fermi mechanism, and the acceleration is due to large-scale gradients in the hydrodynamic velocity of plasma. In particular, the acceleration in shear flows and collisionless shock waves has long been known [1, 3, 10]. As shown in Section 2, ion acceleration to ultrahigh energies is easier to ensure in ultrarelativistic flows.

While on the subject of the Fermi mechanism, the so-called stochastic acceleration is commonly implied. To estimate the suitability of this mechanism for the generation of ultrahigh-energy cosmic rays, we recall its scheme by the example of a shock wave. In a collisionless plasma, particles interact with each other via the magnetic field produced by the currents flowing through the plasma. The magnetic field is frozen into the plasma on both sides of the shock front, where the hydrodynamic plasma velocity experiences a jump; therefore, for a particle with a sufficiently long mean free path (i.e., with a sufficiently large momentum), the transit through the front is like a collision with a moving wall. The particles may either gain energy or lose it, depending on the direction of its motion, but on average the energy increases. This acceleration is similar to gas heating in a vessel with approaching walls, with the only difference that there is no second wall to reflect the particles back towards the shock front. Long-term acceleration and a substantial energy gain are possible only for the particles that can repeatedly cross the shock front in the opposite direction by overtaking it due to diffusive motion in the nonuniform magnetic field.

The average statistical particle acceleration rate in a nonrelativistic shock increases proportionally to the square of its velocity. The higher the velocity, the higher the maximum energy of accelerated particles. However, in a relativistic shock wave whose velocity is close to the speed of light, the acceleration mechanism considered above turns out to be inefficient. There are two reasons for this. First, the hydrodynamic velocity of the flow behind the front of a relativistic shock wave is equal to one third of the speed of light, and therefore the regular motion of particles prevails over their diffusive displacement and they have little chance to return to the front and continue their acceleration. Second, the plasma compression in the shock wave has the effect that the component of the frozen-in magnetic field parallel to the front increases, while the perpendicular component remains invariable. As a result, the particle drift velocity in the nonuniform magnetic field is directed approximately parallel to the front and the particles describe cycloids that do not cross the front. These theoretical considerations are borne out by numerical simulations [18, 19].

Efficient particle acceleration in relativistic shock waves and shear flows is nevertheless possible [5]. Paradoxically, the main role is here played by the interaction of accelerated particles with photon fields in accelerators, which is ordinarily regarded merely as an impediment, an additional channel of energy loss. Under certain conditions, collisions with photons may be treated as a mechanism of random 'activation' and 'deactivation' of the electric charge. The acceleration scheme described above is then modified as follows (Fig. 3). When traversing the shock front and experiencing reflections from the inhomogeneities of the magnetic field, a charged particle increases its energy to become neutral upon interacting with a photon, which allows it to traverse the front in the opposite direction unhindered by the magnetic field. On finding itself in front of the shock wave, the particle comes to be charged once again, such that the whole acceleration cycle is repeated over and over again. This particle acceleration mechanism may be termed the converter mechanism; calculations show that it plays a crucial role in the radiation and dynamics of relativistic flows [5, 6, 20].

Of course, the activation and deactivation of electric charge is no more than a conventional way of describing the processes occurring. For instance, we trace the chain of transformations beginning with the interaction of a proton with a high-energy gamma-ray photon. The photons whose energy exceeds 300 MeV in the rest frame of the proton can excite its internal (quark) degrees of freedom. The cross section of this process rapidly attains its peak $\sigma_\pi \approx 6 \times 10^{-28}$ cm^2 for the photon energy $\Delta_p \approx 340$ MeV (which may be considered the effective threshold of the reaction) and gradually decreases to $\approx 10^{-28}$ cm^2 for extremely energetic photons. The resultant excited hadron (typically, a Δ resonance) almost instantaneously decays into a nucleon and a pion:

$$\mathrm{p} + \gamma \to \Delta \to \mathrm{n} + \pi^+ \tag{13}$$

or

$$\mathrm{p} + \gamma \to \Delta \to \mathrm{p} + \pi^0 . \tag{14}$$

In approximately one-third of the cases, a charged pion forms and the proton transforms into a neutron. Neutrons have the

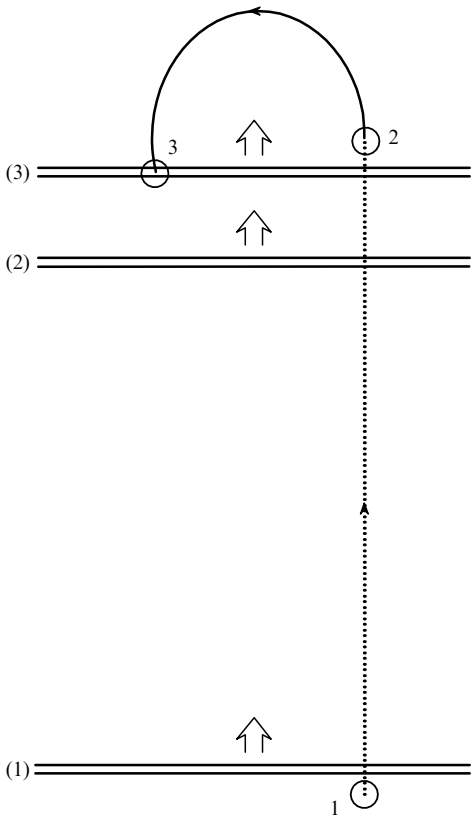

Figure 3. In the converter acceleration mechanism, a particle escapes from the shock wave being neutral (time instant 1) and travels rectilinearly until the moment it transforms to the charged one (time instant 2). During this time, the particle overtakes the shock front by some distance and therefore gains a sufficient store of time to start moving in the opposite direction in the magnetic field before it is entrained by the shock once again (time instant 3). The particle and shock front positions at the corresponding instants are numbered 1, 2, and 3.

same quark structure and interact with photons by the same scheme, i.e., transforming to protons. A by-product of the proton – neutron cycle is high-energy charged pions, whose decay gives rise to secondary electrons and positrons, as well as neutrino radiation.

A similar transformation chain also exists for electrons. It begins with photon scattering from a relativistic electron. As a result of the inverse Compton effect (comptonization), the photon energy upon scattering is many times higher, but for Thomson scattering, it amounts to only a small fraction of the electron energy. This interaction gradually takes energy from the electrons and does not favor their acceleration. However, the broadband radiation spectrum of cosmic accelerators also involves high-frequency photons scattered in the Klein – Nishina regime. In this case, the comptonized radiation spectrum has two peaks: with equal probabilities, an electron either retains the major part of its energy or transfers it to the photon. In the latter case, it can be said that the accelerated particle changes its charge, because the photon produced travels in the same direction as the initial electron and carries almost all of its energy. The high-energy comptonized photons interact with the relatively low-frequency background radiation to produce electron – positron pairs, the energy being approximately equally distributed between an electron and a positron. The transformation chain described above results in the closed cycle of activation and deactivation of accelerated particle charge. The fact that the number of accelerated particles doubles is of no fundamental importance. The converter acceleration of electrons and positrons has no direct bearing on the origination problem of ultrahigh-energy cosmic rays. We note, however, that the radiation of particles accelerated by this mechanism exhibits unique features (see Section 4): when recorded in the emission of some astrophysical object, they allow judging whether the converter mechanism operates in the object.

The small cross section of photopion reactions is the main limiting factor for the converter acceleration. The most favorable conditions for its realization exist in active galactic nuclei and gamma-ray bursts, where both ultrarelativistic matter flows in the form of jets and dense photon fields simultaneously exist (see review Refs [21, 22]).

The optical thickness τ that characterizes the accelerated-particle interaction with photons depends on the source geometry. For a continuous flow or a shock wave produced by a central compact object and propagating with an angular opening greater than $1/\Gamma$, we have

$$\tau \approx \frac{\sigma_\pi L(\varepsilon_*)\,\Theta^2}{4\,\pi R c \varepsilon_*}\,, \tag{15}$$

where L is the observed luminosity per logarithmic frequency interval for photons with energies in the vicinity of $\varepsilon_* = 2\,mc^2\Delta_\mathrm{p}/(\varepsilon\,\Theta^2)$, where the nucleon – photon interaction is most efficient, ε is the energy of the accelerated particle, R is the distance to the central object, Γ is the Lorentz factor of the relativistic flow, and m is the nucleon mass. The beam pattern of the photon source has the width $\Theta \sim 1/\Gamma$ for jets and $\Theta \sim 1$ for regions with broad emission lines in active galactic nuclei or for radiation scattered by the interstellar gas in the vicinity of gamma-ray bursts.

We give estimates for three qualitatively different cases. For internal jets in active galactic nuclei (with the inclusion of only the intrinsic radiation of the jet with $\Theta = 1/\Gamma$), where the observed luminosity $L(\varepsilon_*)$ per logarithmic frequency interval is implicitly dependent on the particle energy, we have

$$\tau \approx 10^{-1}\left(\frac{L(\varepsilon_*)}{10^{45}\,\mathrm{erg\,s^{-1}}}\right)\left(\frac{\varepsilon}{10^{18}\,\mathrm{eV}}\right)\left(\frac{10}{\Gamma}\right)^4\left(\frac{10^{15}\,\mathrm{cm}}{R}\right). \tag{16}$$

Radiation from regions with broad emission lines in active galactic nuclei produces the optical depth

$$\tau \sim 5\times 10^{-2}\left(\frac{L}{10^{44}\,\mathrm{erg\,s^{-1}}}\right)\left(\frac{10\,\mathrm{eV}}{\bar{\varepsilon}}\right)\left(\frac{10^{17}\,\mathrm{cm}}{R}\right), \tag{17}$$

which is independent of the particle energy: for all particles with energies $\varepsilon > 2\,mc^2\Delta_\mathrm{p}/\bar{\varepsilon} \approx 5\times 10^{16}$ eV, the number of effectively interacting photons is invariable due to their narrow spectral distribution (primarily in the vicinity of $\bar{\varepsilon} \sim 10$ eV). In gamma-ray bursts, the optical depth is

$$\tau \approx 3\times 10^{-3}\left(\frac{E(\varepsilon_*)}{10^{52}\,\mathrm{erg}}\right)\left(\frac{\varepsilon}{10^{16}\,\mathrm{eV}}\right)\left(\frac{100}{\Gamma}\right)^2\left(\frac{10^{16}\,\mathrm{cm}}{R}\right)^2. \tag{18}$$

Therefore, the conversion probability in every cycle is ordinarily much lower than unity. There are exceptions, for instance, at the base of a relativistic flow, where the optical thickness is large and conversion losses suppress acceleration. But as the distance from the jet base increases, acceleration

becomes possible once again and encompasses particles with a progressively higher energy as the radiation density decreases to the extent that the conversion probability in a single acceleration cycle becomes appreciably lower than unity. It is clear from the aforesaid that the converter acceleration is self-tunable.

We note that the neutron-to-proton conversion probability is always higher than

$$p_{\rm cn}^{(\min)} = \frac{Rmc}{t_{\rm n}\varepsilon} \approx 3\times 10^{-2}\left(\frac{10^{15}\,{\rm eV}}{\varepsilon}\right)\left(\frac{R}{10^{18}\,{\rm cm}}\right) \qquad (19)$$

owing to spontaneous neutron decay. Here, $t_{\rm n} \approx 900$ s is the free-neutron lifetime. The decay is important for low-energy particles, especially in the first acceleration cycle, whereas photopion reactions are more effective at high energies.

4. Features of the energy gain and radiation by particles during converter acceleration

The converter acceleration mechanism enables particles to attain the energy 10^{20} eV in only 2–4 passages through the shock front. For the standard diffusive acceleration, this would require many dozens of passages; the difficulties of realizing this mechanism are accordingly multiplied. This distinction may be explained as follows.

The velocity of particles that escape from the relativistic shock wave is, in the rest-frame system, directed almost parallel to the velocity of the shock wave. But the trajectory of charged particles immediately starts to bend under the action of a magnetic field. As soon as the angle between the particle velocity and the direction of the shock propagation attains a value of the order of the inverse Lorentz factor, the shock front catches up with the escaping particle and completes the acceleration cycle. The cycle result is that the particle energy increases twofold on average.

In the case of converter acceleration, a particle leaves the shock wave being neutral and travels rectilinearly until the instant of its transformation into a charged particle. During this time, the particle overtakes the shock front by some distance and hence acquires a sufficient time reserve to turn towards the shock wave in the magnetic field before it is entrained by the shock once again. Therefore, a converter acceleration cycle has the result that the particle energy increases not twofold but by about the factor γ^2, where γ is the Lorentz factor of the shock wave.

The probability that the particle converting from charged to neutral and backwards occurs in the right sequence and the particles interact with photons that have the appropriate energy is much lower than unity. On the other hand, the energy of a particle that goes through a complete acceleration cycle increases by a factor $g \sim \Gamma^2$, which ranges from several hundred for jets in active galactic nuclei to several hundred thousand for gamma-ray bursts. Upon experiencing several acceleration cycles, the initial quasimonoenergetic injected-particle distribution transforms into a saw-tooth distribution (Fig. 4). Its envelope may be approximately represented as a power-law function $\mathrm{d}N/\mathrm{d}\varepsilon \propto \varepsilon^{-\alpha}$ with the exponent

$$\alpha = 1 - \frac{\ln k}{\ln g}\,, \qquad (20)$$

which depends only slightly on the particle energy. When the cycle pass-through probability k times the energy gain factor g exceeds unity, the converter mechanism peaks in efficiency:

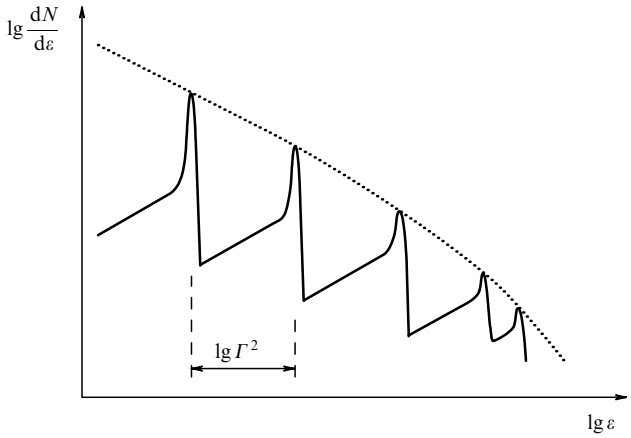

Figure 4. Schematic view of the particle distribution (solid line) resulting from the converter acceleration for a quasimonoenergetic injection. The dips in the spectrum persist as long as the width of the injection spectrum in logarithmic units is less than $\lg \Gamma^2$.

the total energy content in accelerated particles increases every cycle, the main contribution being due to particles whose energy is close to the maximum attainable energy.

The shock front can be crossed in the opposite direction only by the particles that manage not to lose energy (for instance, by synchrotron radiation) in the time required to complete a half-turn in the magnetic field behind the front. The particles that lose half of their energy during this turn are termed critical. In the diffusive acceleration, the particle energy increases approximately twofold in each cycle (except for the first one), and therefore the critical energy is also the highest attainable, whereby the energy loss rate is comparable to the acceleration rate.

Although the energy of particles escaping from the shock wave is bounded by the critical value, the energy of particles fed to the shock from the outside may be many times higher. Supercritical particles lose energy on traveling a distance many times shorter than their gyroradius, i.e., being deflected only slightly from the initial direction of their travel [almost strictly backwards in the frame of reference comoving with the matter behind the shock front (Fig. 5)]. Accordingly, the supercritical-particle radiation beam pattern is strongly elongated in the direction opposite to the shock velocity, as is the particle velocity distribution in the frame of reference of the jet [6]. Due to the relativistic aberration of light, a rest-frame observer nevertheless sees the beam pattern elongated in the direction of jet motion, but it turns out to be significantly broader than the beam pattern of the lower-frequency radiation of subcritical particles. Radiation of supercritical particles, which is primarily confined to the X- and gamma-ray ranges, may be observed at a large angle to the jet axis, i.e., it is off-axial (see Fig. 5).

The occurrence of off-axial radiation explains, for instance, the phenomenon of delayed hard radiation of gamma-ray bursts. The delay in this case is geometrical in nature: owing to the broadened radiation beam pattern, the off-axial emission is observed from a broader segment of a spherical shock wave, whose rim is more distant from the observer than its central part. The radiation beam pattern broadening may also account for detection of so-called unidentified sources of hard gamma-ray radiation (a large number of such sources were discovered by the EGRET

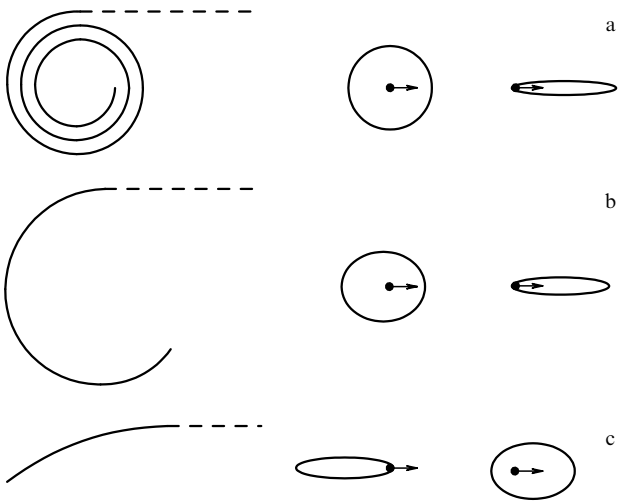

Figure 5. Variation of the radiation beam pattern in moving from subcritical (a) to critical (b) and then to supercritical (c) particle energy. The left part of the picture shows conventional particle trajectories during the radiation of half their energy, the central part shows typical radiation beam patterns in the comoving frame of reference, and the right part depicts typical radiation beam patterns in the laboratory frame of reference.

(Energetic Gamma Ray Experiment Telescope) space telescope in 1992 – 1994). These sources are supposedly related to those quasars whose jets are oriented at large angles to the line-of-sight direction and therefore do not produce appreciable radiation in lower-frequency ranges, where the jet emission is highly directional. High-energy neutrino emission of accompanying the decay of pions produced in inelastic proton – neutron collisions in relativistic jets may also have a broad beam pattern.

5. Conclusion

We have considered the fundamental bounds for the cosmic accelerator parameters. They indicate that the production of cosmic rays with energies ranging up to the highest reliably observed values is possible (at least theoretically) due to the action of the electromagnetic fields of astrophysical objects on the relatively low-energy ions present in these objects. There also exists an acceleration mechanism involving alternate conversion of protons to neutrons and back. This mechanism is operable in a broad class of sources with relativistic flows and is capable of transferring the power of these flows to $\sim 10^{20}$ eV cosmic rays with the efficiency approaching 100%. Therefore, it is possible to interpret all presently existing observations of ultrahigh-energy cosmic rays without invoking 'new physics,' i.e., using only reliably established physical laws and astrophysical facts.

Estimates show that different regions in the relativistic jets in active galactic nuclei, shock waves in galaxy clusters, and gamma-ray bursts may 'aspire' to play the role of accelerators for particles with an energy $\lesssim 10^{20}$ eV. With the exception of gamma-ray bursts, these all are galactic-scale objects. In particular, neutron stars and black holes, including the supermassive ones, cannot be the sources of cosmic rays.

Finally, we dwell on the validity range of the origination picture of ultrahigh-energy cosmic rays outlined in this report. The converter acceleration mechanism leads to a specific prediction about the particle composition of cosmic rays: these particles should be protons and nothing but protons. The existing data argue in favor of this proposition, although an unambiguous conclusion cannot be reached at the moment. If future observations reveal the presence of a substantial fraction of atomic nuclei in ultrahigh-energy cosmic rays, there will be no way of explaining their origin on the basis of the converter mechanism. But it is not inconceivable that there exists a different, and yet equally efficient, particle acceleration mechanism.

We have shown, however, that general electrodynamic considerations lead to a very strong dependence of the required field energy in an accelerator on the energy of the particles it produces, irrespective of the acceleration mechanism. For the known astrophysical objects, the acceleration limit for protons is therefore $(3-5) \times 10^{21}$ eV in the framework of the canonical model of cosmic ray generation. In this case, the list of potential sources is restricted to hot spots in the jets of active galactic nuclei, radio lobes, and galaxy clusters. In all these cases, the acceleration is limited by the particle escape, and attaining the specified energy value is possible only under rather speculative assumptions about large-scale magnetic field ordering and the high dimensionless acceleration rate $\eta \approx 1$. Heavy nuclei may be accelerated to even higher (Z times) energies, such that the acceleration scenario can formally account for the cosmic rays ranging up to 10^{23} eV in energy. At the same time, owing to the fragmentation of the nuclei (in the interaction with the photons of the microwave background radiation) their propagation distance is bounded by ~ 1 Mpc. Gamma bursts are the only sources in so close a neighborhood of our galaxy, and hence the highest cosmic ray energy observable on the earth cannot exceed the somewhat lower value $\sim 3 \times 10^{22}$ eV, which corresponds to the limit of acceleration in gamma-ray bursts for iron nuclei (for protons, this limit is $\sim 10^{21}$ eV).

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Modification of the earth's ionosphere by high-power high-frequency radio waves

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1. Introduction

The ionosphere, being the upper part of the terrestrial atmosphere, has a decisive effect on both the nature of vital functions on Earth and the properties of different tele- and radio communication channels. In this connection, it has attracted the close attention of researchers already for many decades. The range of ionospheric research is extremely wide and embraces problems such as the physics of plasma formation, plasma dynamics and the mechanisms of plasma turbulization, ionospheric chemistry, and the propagation of radio waves in different ranges. The capabilities of conventional methods of ionospheric research were greatly enhanced when active ionospheric experiments were started. These include plasma modification by high-power radio wave beams produced by ground-based and space-borne high-frequency (HF) radio transmitters, as well as the injection of charged particle beams and chemical reagents from aboard artificial earth satellites (AESs) and geophysical rockets. The success achieved in active experiments allowed considering the ionosphere as a natural space laboratory for modeling different processes occurring in plasmas [1]. The relatively high stability and the practically infinite volume of the ionospheric plasma, as well as the variation over a wide range in its possible parameter values, permit a broad class of currently topical problems to be solved on an experimental basis.

The variation in ionospheric properties in the field of high-power radio waves was first encountered over 70 years ago in connection with the discovery of the Luxemburg–Gorky effect in 1933 [2]. The decisive roles in the theoretical interpretation of this effect were played by Ginzburg, Gurevich, and Vilenskii. The explanation of the Luxemburg–Gorky effect led to the understanding of the role of the nonlinear properties of ionospheric plasma, which show up under heating by a high-power radio wave and were considered at length by Ginzburg and Gurevich in Ref. [3]. The investigations conducted lent impetus to the construction of special-purpose high-power heater facilities for the modification of the ionosphere. In the USSR, the first facility was put into operation in the Scientific Research Radio Institute (Moscow) in 1961. More recently, constructed in the USA were the facilities Boulder in 1970 and Arecibo in 1971. At the Radiophysical Research Institute (NIRFI), this line of investigation was initiated by Getmantsev. Under his supervision, the Zimenki facility was constructed in 1973 near Nizhnii Novgorod (formerly the city of Gorky). In 1976, the Polar Geophysical Institute (PGI) of the Kola Branch of the USSR Academy of Sciences succeeded in its efforts to construct the Monchegorsk facility in polar latitudes near Murmansk.

Already in the first experiments on ionospheric modification by high-power radio waves carried out in the 1960s–1970s, apart from the expected large-scale variations in plasma temperature and density, several new phenomena related to the generation of artificial plasma oscillations and artificial plasma density irregularities with scale lengths ranging from fractions of a meter to several kilometers transversely to the geomagnetic field were discovered [4, 5], the Getmantsev effect was discovered [6], and the formation of artificial periodic irregularities of ionospheric plasma density in the field of a high-power standing radio wave was experimentally borne out [7]. There emerged a new line of research, which soon became one of high-priority areas in radiophysics and found diversified uses in geophysics, plasma physics, and space physics. An important point is that modifying the ionosphere by high-power radio waves does not pollute the environment and has no undesirable ecological consequences, because this action on the ionosphere is negligible in power in comparison with natural actions. At the same time, the possibility exists of conducting repeated measurements of the characteristics of the upper terrestrial atmosphere on a regular basis by using the thoroughly elaborated radiophysical techniques for the remote diagnostics of artificially produced plasma perturbations.

The results achieved fostered the construction of new, more powerful heaters in northern Norway (Tromsø, 1980) and in the USSR (Sura, 1981). More recently, in the 1990s, a start was made on the construction of a facility in Alaska (USA) in the framework of the High Frequency Active Auroral Research Program (HAARP); its first stage was put into service in the late 1990s. To this day, efforts are directed towards upgrading the potentialities of the facility. Among other facilities constructed in the 1980s–1990s are Gissar (Tadjikistan, 1981), a facility near Kharkov (Ukraine, 1987), and the High Power Auroral Simulation (HIPAS) facility (USA, 1990). Today, experiments in the modification of the ionosphere are conducted primarily at three facilities: HAARP and Tromsø in polar latitudes and Sura in middle latitudes. The remaining facilities either have fallen apart or are no longer in active use. In recent years, the British have undertaken the construction of the SPEAR (Space Plasma Exploration by Active Radar) facility on the island of Spitsbergen, in the polar cap zone. In 2004, the first stage of SPEAR was put into operation and heater experiments were started.

In this report, we briefly outline the results of experiments in artificial influence on the ionosphere by high-power HF