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TeV SIGNATURES OF COMPACT UHECR ACCELERATORS

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We numerically study particle acceleration by the electric field induced near the horizon of a rotating supermassive ($M \sim 10^9$–$10^{10} M_\odot$) black hole embedded in the magnetic field B. We find that acceleration of protons to the energy $E \sim 10^{20}$ eV is possible only at extreme values of M and B. We also find that the acceleration is very inefficient and is accompanied by a broad-band MeV–TeV radiation whose total power exceeds the total power emitted in ultra-high energy cosmic rays (UHECR) at least by a factor of 1000. This implies that if $O(10)$ nearby quasar remnants were sources of proton events with energy $E > 10^{20}$ eV, then each quasar remnant would, e.g., overshine the Crab nebula by more than two orders of magnitude in the TeV energy band. Recent TeV observations exclude this possibility. A model in which $O(100)$ sources are situated at 100–1000 Mpc is not ruled out and can be experimentally tested by present TeV γ-ray telescopes. Such a model can explain the observed UHECR flux at moderate energies $E \approx (4–5) \cdot 10^{19}$ eV.

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1. INTRODUCTION

The conventional hypothesis of ultrahigh-energy cosmic ray (UHECR) acceleration in extragalactic astrophysical objects has two important consequences. First, it predicts the Greisen–Zatsepin–Kuzmin (GZK) cutoff [1] in the spectrum of UHECR at energy of the order $5 \cdot 10^{19}$ eV. Whether such a cutoff indeed exists in nature is currently an open question [2, 3]. Second, it implies that the observed highest-energy cosmic rays with $E > 10^{20}$ eV should come from within the GZK distance ~ 50 Mpc. Moreover, under plausible assumptions about extragalactic magnetic fields supported by recent simulations [4], the propagation of UHE protons over the GZK distance is rectilinear and the observed events should point back to their sources. While sub-GZK UHECR were found to correlate with BL Lacertae objects [5, 6], no significant correlations of cosmic rays with energies $E \gtrsim 10^{20}$ eV with nearby sources were found [7].

In view of the last problem, a question arises whether there exist UHECR accelerators that can produce super-GZK protons and are quiet in the electromagnetic (EM) channel. If such quiet accelerators existed, they could explain the apparent absence of sources within ~ 50 Mpc in the direction of the highest-energy events. This idea was advocated, e.g., in Ref. [8], where sources of UHE protons were associated with supermassive black holes in quiet galactic nuclei (the so-called «dead quasars»). However, it was pointed out in [9] that most of the energy available for particle acceleration in such an environment is spent for EM radiation by the accelerated particles. As a consequence, the flux of TeV γ-rays produced by such an accelerator may be at a detectable level.

Recent observations by HEGRA/AIROBICC [10], MILAGRO [11] and TIBET [12] arrays substantially

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improved the upper limits on the flux of γ-rays above 10 TeV from the point sources in the Northern hemisphere. This may completely exclude a possibility to explain the observed super-GZK cosmic rays by the acceleration near supermassive black holes. The purpose of this paper is to analyze this question quantitatively. For this, we study particle acceleration near the black hole horizon numerically. Following Refs. [8, 9], we restrict ourselves to the case of protons. The case of heavy nuclei acceleration, propagation, and detection is phenomenologically very different and requires separate consideration. In particular, heavy nuclei can be easily desintegrated already at the stage of acceleration.

We stress that our purpose is not to construct a realistic model of a compact UHE proton accelerator but to find whether quiet compact accelerators may exist, even if most favorable conditions for the acceleration are provided. For this, we minimize the energy losses of accelerated particles by considering acceleration in the ordered electromagnetic field and neglect all possible losses related to scattering of the accelerated particles on matter and radiation present in the acceleration site. However, we self-consistently take into account the synchrotron/curvature radiation losses, which are intrinsic to the acceleration process. Clearly, this approximation corresponds to most favorable conditions for particle acceleration. In realistic models, the resulting particle energy must be smaller and the emitted EM power larger. Therefore, our results should be considered as a lower bound on the ratio of the electromagnetic to UHECR power of a cosmic ray accelerator based on a rotating supermassive black hole.

We find that the flux produced by a nearby UHE proton accelerator of super-GZK cosmic rays in the energy band $E_\gamma > 10$ TeV should be at least 100–1000 times larger than that of the Crab nebula. The existence of such sources is indeed excluded by recent observations [10, 11]. At the same time, the constraints on the sources of sub-GZK cosmic rays are weaker or absent, see Sec. 7 for details.

This paper is organized as follows. In Sec. 2, we describe our minimum-loss model in more detail. In Sec. 3, we present the analytical estimate and the numerical calculation of the maximum particle energy. In Sec. 4, the self-consistency constraints on the parameters of this model are considered that arise from the requirement of the absence of the on-site e^+e^- pair production caused by emitted radiation. In Sec. 5, the calculation of the EM luminosity of the accelerator is presented. In Sec. 6, observational constraints are derived. Section 7 contains a discussion of the results and concluding remarks.

2. THE MODEL

The model that we consider is based on a rotating supermassive black hole embedded in a uniform magnetic field. Because of the rotational drag of magnetic field lines, an electric field is generated, leading to acceleration of particles. In the absence of matter, the corresponding solution of the Einstein – Maxwell equations is known analytically at arbitrary inclination angle of the black hole rotation axis with respect to the magnetic field [13, 14]. We assume low accretion rate and small matter and radiation density near the black hole, and neglect their back reaction on the EM and gravitational fields. We also neglect the effect of matter on propagation of the accelerated protons. This corresponds to the most favorable conditions for particle acceleration, and therefore leads to a maximum proton energy and minimum EM radiation.

The model has three parameters: the black hole mass M, the strength of the magnetic field B, and the inclination angle χ. We consider the maximally rotating black hole with the rotation moment per unit mass $a = M$. This maximizes the strength of the rotation-induced electric field. For a given injection rate and geometry, the above parameters completely determine the trajectories of accelerated particles and, therefore, their final energies and the emitted radiation. We reconstruct particle trajectories numerically keeping track of the emitted radiation and taking its back reaction onto particle propagation into account.

We assume that protons flow into the acceleration volume from the accretion disk that is situated at larger radii. We model this accretion by injecting nonrelativistic particles uniformly over the sphere of the Schwarzschild radius $R_S = 2GM$, which is two times larger than the horizon of the maximally rotating black hole. We follow the trajectories of particles that propagate toward the horizon and are then expelled from the vicinity of the black hole with high energies. It turns out that such trajectories exist only if the inclination angle of the magnetic field with respect to the rotation axis is large enough, $\chi \gtrsim 10°$. For smaller inclination angles, all particles that propagate toward the horizon are finally absorbed by the black hole. This means that the stationary regime in which particles accreted onto the black hole are subsequently accelerated and ejected with high energies exists only at $\chi \gtrsim 10°$. In this regime, changes of the inclination angle and the injection radius do not strongly affect the maximum energies of particles.

3. MAXIMUM PARTICLE ENERGIES IN THE STATIONARY REGIME

In the abscence of matter and radiation backgrounds, particle energies are limited by the radiation loss intrinsic to the acceleration process. For a general electric and magnetic field configuration, the energy loss in the ultrarelativistic limit is given by [15]

$$\frac{d\mathcal{E}}{dt} = -\frac{2e^4\mathcal{E}^2}{3m^4}\left[(\mathbf{E}+\mathbf{v}\times\mathbf{B})^2-(\mathbf{E}\cdot\mathbf{v})^2\right], \quad (1)$$

where m, e, and $\mathbf{v}$ are particle mass, charge, and velocity, respectively. We use this equation in our numerical modeling to calculate the electromagnetic radiation produced by the accelerated particles and to account for the back reaction of this radiation on particle trajectories.

Before presenting the numerical results, it is useful to summarize some simple qualitative estimates, see, e.g., [9, 16, 17]. We consider particle acceleration by a generic electromagnetic field obeying $|\mathbf{E}| \sim |\mathbf{B}|$. If the energy losses can be neglected, energies of accelerated particles are estimated as

$$\mathcal{E} = eBR \approx 10^{22}\frac{B}{10^4\ \text{G}}\,\frac{M}{10^{10}M_\odot}\ \text{eV}, \quad (2)$$

where we assume that the size R of the acceleration region is of the order of the gravitational radius of the black hole, $R \approx 2GM$. But if the magnetic field strength is high, the synchrotron/curvature energy losses cannot be neglected.

If no special relative orientation of the three vectors $\mathbf{E}$, $\mathbf{B}$, and $\mathbf{v}$ is assumed, Eq. (1) becomes

$$\frac{d\mathcal{E}}{dt} \approx -\frac{2e^4B^2\mathcal{E}^2}{3m^4}, \quad (3)$$

which is the standard formula for the synchrotron energy loss. Equating the rate of energy gain $d\mathcal{E}/dt = eE \sim eB$ to the rate of energy loss, we find that in the synchrotron-loss-saturated regime, the maximum energy is given by (see, e.g., [18])

$$\mathcal{E}_{syn} = \left(\frac{3m^4}{2e^3B_0}\right)^{1/2} \approx \approx 1.6\cdot 10^{18}\left(\frac{B}{10^4\ \text{G}}\right)^{-1/2}\ \text{eV}. \quad (4)$$

Here, we assume that accelerated particles are protons; for electrons, the maximum energy is much smaller.

The critical magnetic field strength at which the synchrotron energy loss becomes important can be found from the condition that estimates (2) and (4) give the same result,

$$B_{crit} = \left(\frac{3m^4}{2e^5R^2}\right)^{1/3} \approx 30\left(\frac{M}{10^{10}M_\odot}\right)^{-2/3}\ \text{G}. \quad (5)$$

Here, it is assumed that $R \sim R_S$. This critical field corresponds to the particle energy

$$\mathcal{E}_{crit} \approx 3\cdot 10^{19}\left(\frac{M}{10^{10}M_\odot}\right)^{1/3}\ \text{eV}, \quad (6)$$

which is a maximum energy attainable in the synchrotron-loss-saturated regime for a given black hole mass.

Acceleration is more efficient (loss (1) can be orders of magnitude smaller) in the special case where $\mathbf{E}$, $\mathbf{B}$, and $\mathbf{v}$ are nearly aligned. These conditions may be approximately satisfied in some regions around the black hole. In this case, particles closely follow the curved field lines and the curvature radiation loss,

$$\frac{d\mathcal{E}}{dt} = -\frac{2e^2\mathcal{E}^4}{3m^4R^2}, \quad (7)$$

becomes the main energy loss channel for high-energy particles. For an order-of magnitude estimate, we can assume that the curvature scale of the magnetic field lines is of the order of the size of the acceleration region, $R \approx 2GM$. This translates into the maximum energy

$$\mathcal{E}_{cur} = \left(\frac{3m^4R^2B}{2e}\right)^{1/4}, \quad (8)$$

which gives

$$\mathcal{E}_{cur} = 1.1\cdot 10^{20}\left(\frac{M}{10^{10}M_\odot}\right)^{1/2}\left(\frac{B}{10^4\ \text{G}}\right)^{1/4}\ \text{eV} \quad (9)$$

for protons, where we again set $R = R_S$. The range of applicability of Eqs. (8) and (9) is given by the same condition $B > B_{crit}$.

In the numerical simulations, we injected protons uniformly over the sphere surrounding the black hole. We disregarded trajectories that start at the injection sphere and move outward. Among protons that approach the horizon and are then expelled to infinity, we selected those which have the maximum final energy. For the black hole mass $M = 10^{10}M_\odot$, the dependence of this maximum energy on the magnetic field strength is shown in Fig. 1 (the upper curve). For energies of the order 10^{20} eV and higher, the numerically calculated curve approaches limit (9), which corresponds to the curvature-loss-saturated regime. The acceleration to these energies requires magnetic fields in excess of

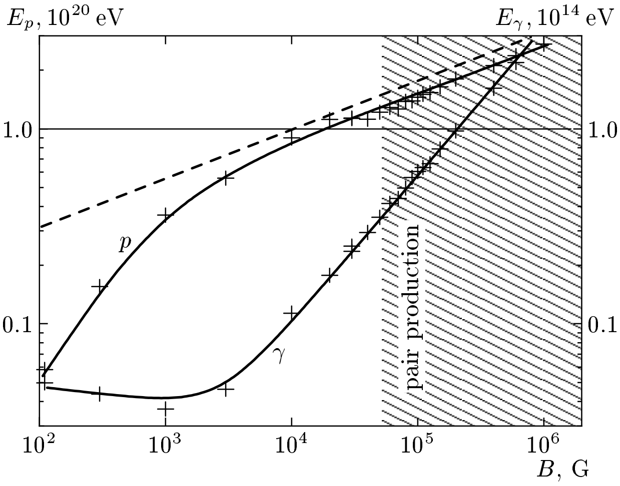

Fig. 1. The results of numerical calculation of maximum energies of accelerated protons and accompanying γ-rays are shown by crosses (solid lines are fits to numerical data). The dashed line is estimate (9) of the proton energies in the curvature-loss dominated regime. The shaded region corresponds to the magnetic field strength exceeding the pair production threshold by the curvature γ-rays. The black hole mass is $M = 10^{10} M_\odot$

10^4 G. The necessary magnetic field is even stronger for smaller black hole masses, cf. Eq. (9). The maximum energies of protons do not depend strongly on the inclination angle in a wide range of χ.

4. CONSTRAINTS FROM PAIR PRODUCTION

There is an important self-consistency constraint that does not allow increasing B and M independently in order to reach higher energies. The reason is as follows. In our model, it was assumed that the acceleration proceeds in the vacuum. However, at a sufficiently strong magnetic field, photons of curvature radiation may produce e^+e^- pairs. Electrons and positrons are in turn accelerated and produce more photons, which again produce e^+e^- pairs, etc. The plasma created by this cascade then neutralizes the electric field and prevents further acceleration of particles. For consistency of the model, we have to require that the cascade does not develop.

We consider this process in more detail. The energy ϵ_γ of the curvature photons in the regime when particle energies are limited by curvature losses is estimated as

$$\epsilon_\gamma = \frac{3\mathcal{E}_{cur}^3}{2m^3 R} \propto B^{3/4} M^{1/2}.$$

(cf. Eq. (8)). Remarkably, the photon energy is independent of the particle mass. This means that proton-originated and electron-originated photons have the same energy. Numerically, we have

$$\epsilon_\gamma \approx 14 \left(\frac{B}{10^4\,\mathrm{G}}\right)^{3/4} \left(\frac{M}{10^{10} M_\odot}\right)^{1/2} \ \mathrm{TeV}. \qquad (10)$$

If this energy is enough to produce more than one e^+e^- pair within the acceleration site, the instability may develop.

Therefore, for the stationary operating accelerator, the mean free path d of a γ-ray in the background of a strong magnetic field (see [19]) has to be larger than the size of the acceleration region

$$d \approx 100 \frac{10^4\,\mathrm{G}}{B} \exp\left(\frac{8m_e^3}{3eB\epsilon_\gamma}\right) \ \mathrm{cm} > R_S. \qquad (11)$$

This requirement leads to the condition

$$B < 3.6 \cdot 10^4 \left(\frac{10^{10} M_\odot}{M}\right)^{2/7} \ \mathrm{G} \qquad (12)$$

on the magnetic field in the vicinity of the horizon.

In the numerical calculation of proton trajectories, we kept track of the emitted photons. For given parameters of the accelerator, we determined the maximum photon energy. The dependence of this energy on the magnetic field strength is shown in Fig. 1 (the lower curve). Substituting the calculated photon energy in Eq. (11), we can check whether the accelerator is in the stationary regime. The shaded region in Fig. 1 corresponds to nonnegligible pair production. The results of numerical calculation are in good agreement with Eq. (12).

From Fig. 1, we conclude that acceleration of protons to energies higher than 10^{20} eV is marginally possible in a small region of the parameter space (M, B). The magnetic field strength B must be close to the pair production threshold. The black hole mass M must be larger than $10^{10} M_\odot$. Such black holes are rare. For example, in Ref. [20], it is found that supermassive black holes in AGNs range in $10^{6.5}$–$10^{10.2} M_\odot$, with the mean mass being $10^{8.9} M_\odot$. The list of nearby (within 40 Mpc) candidates for quasar remnants [21] does not contain black holes with masses above $5 \cdot 10^8 M_\odot$.

Under reasonable assumptions about the black hole mass, the acceleration to energies above 10^{20} eV is impossible in the stationary regime discussed above (no particle production in the acceleration volume). But although the accelerator cannot operate permanently, it is possible that UHECR are produced during «flares», or short episodes of activity of the accelerator, interrupted by discharges. The natural duration of one flare is about the time needed for the charge redistribution and neutralization of the electric field in the acceleration volume to establish. This can be roughly estimated as the light-crossing time $T_{flare} \sim R_S/c \approx 10$ hours for the $3 \cdot 10^9 M_\odot$ black hole. During such flares, the electromagnetic luminosity of the accelerator must be much higher than the luminosity produced in the stationary regime, because the electromagnetic flux is dominated by the radiation produced by e^+e^- pairs whose number density is much higher than the density of the initial protons. Because we are interested in the possibility of having a «quiet» UHE proton accelerator, we concentrate in the next section on the case of the stationary regime, with the parameteres of the model tuned to $B \approx 3 \cdot 10^4$ G, $M \approx 10^{10} M_\odot$.

5. ELECTROMAGNETIC LUMINOSITY OF THE ACCELERATOR

It is clear from Fig. 1 that the acceleration of protons to energies above 10^{20} eV proceeds in the curvature-loss-saturated regime. In this regime, most of the work done by the accelerating electric field is spent on the emission of curvature radiation rather than on the increase of particle energy. The ratio of the dissipated energy to the final energy of proton is

$$\mathcal{R} \approx \frac{eBR}{\mathcal{E}_{cur}} \approx \approx 2 \cdot 10^2 \left(\frac{M}{10^{10} M_\odot}\right)^{1/2} \left(\frac{B}{3 \cdot 10^4\ \mathrm{G}}\right)^{3/4}. \quad (13)$$

Thus, the energy carried away by photons is at least hundred times higher than the energy carried by cosmic rays. Because only a small fraction of the accelerated protons reaches the UHECR energies $\mathcal{E} \geq 10^{20}$ eV, the ratio of the electromagnetic luminosity of the accelerator to its luminosity in UHECR with $E > 10^{20}$ eV is even higher.

Numerically, we calculated this ratio as follows. We summed energies of those protons which were accelerated above 10^{20} eV, and summed the energy emitted in synchrotron/curvature radiation (including the radiation emitted by protons that did not acquire sufficient energy while being expelled to infinity). We then took the ratio of the two sums.

The results of numerical calculation of the ratio of the electromagnetic and UHECR luminosities in the stationary regime are shown in Fig. 2 by crosses. Variations are due to fluctuations in the precise positions of the injection points[1)]. The qualitative behavior of the numerical results is easy to understand. Close to the «threshold» $\mathcal{E} = 10^{20}$ eV, the accelerator emits a finite power L_{EM} but does not produce UHECR with $\mathcal{E} > 10^{20}$ eV. Therefore, the ratio L_{EM}/L_{UHECR} diverges as $\mathcal{E} \to 10^{20}$ eV. If the magnetic field is large, the maximum energies of particles increase as well. But the ratio $\mathcal{R}$ also increases for each particle according to Eq. (13), and so does L_{EM}/L_{UHECR}. The minimal value of L_{EM}/L_{UHECR} is reached at $\mathcal{E} \approx 1.5 \cdot 10^{20}$ eV. The numerically calculated minimum of L_{EM}/L_{UHECR} is by a factor of 10 larger than estimate (13).

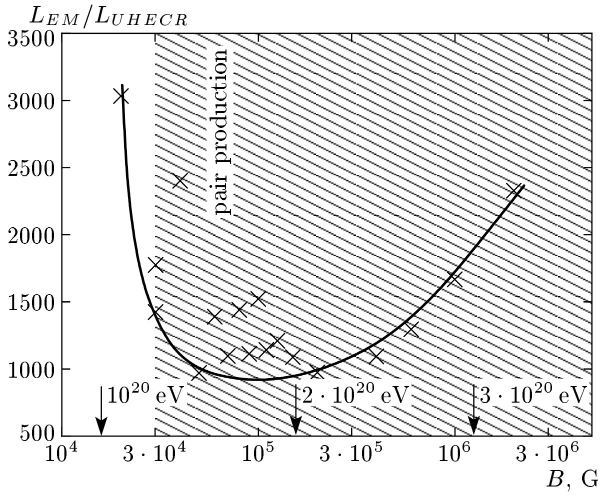

Fig. 2. Numerically calculated ratio of the electromagnetic luminosity of the accelerator to the luminosity emitted in particles with energies $\mathcal{E} \geq 10^{20}$ eV is shown by crosses, with the solid line being the fit to the numerical results. The shaded region corresponds to the magnetic field strength above the threshold of pair production by the curvature γ-rays. The black hole mass is $M = 10^{10} M_\odot$

In obtaining the results in Fig. 2, we have taken only the curvature radiation produced by protons into account. For the magnetic field strength above the pair production threshold $\sim 3 \cdot 10^4$ G (and, correspondingly, $\mathcal{E}_{max} > 1.3 \cdot 10^{20}$ eV, see Fig. 1), our results give the lower bound on the electromagnetic luminosity of the compact accelerator.

We can see from Fig. 2 that the electromagnetic luminosity of the UHE proton accelerator based on a rotating supermassive black hole is

1) For this calculation, we performed injection in 10^3 randomly chosen points uniformly distributed over the sphere.

$$L_{EM} \gtrsim 10^3 L_{UHECR} . \quad (14)$$

Because the typical energy of photons of curvature radiation is about 10 TeV (see Eq. (10)), the above relation implies that such a source of UHE protons would be much more powerful in the 10 TeV band than in the UHECR channel.

6. OBSERVATIONAL CONSTRAINTS

The fact that production of UHE protons in a «quiet» accelerator is accompanied by the emission of the TeV γ-ray flux enables us to put strong constraints on the possibility of existence of such accelerators in the nearby Universe. Following Ref. [8], we assume that there are about $N \sim 10$ nearby UHECR accelerators not farther than $D_{GZK} \sim 50$ Mpc from the Earth. If these sources give the major contribution to the flux of cosmic rays above 10^{20} eV [22],

$$F_{UHECR}^{tot} \sim (2\text{–}6) \cdot 10^{-11} \; \frac{\text{erg}}{\text{cm}^2 \cdot \text{s}},$$

the mean energy flux produced by each source is

$$F_{UHECR} \sim \frac{F_{UHECR}^{tot}}{N} \sim (2\text{–}6) \cdot 10^{-12} \; \frac{\text{erg}}{\text{cm}^2 \cdot \text{s}}. \quad (15)$$

We have seen in the previous section that the lower bound on the ratio of the electromagnetic and UHECR luminosities of such a source is $\mathcal{R} > 10^3$. This means that the electromagnetic flux from the source must be

$$F_{EM} > (2\text{–}6) \cdot 10^{-9} \, \frac{10}{N} \, \frac{\text{erg}}{\text{cm}^2 \cdot \text{s}}, \quad (16)$$

which implies the total luminosity larger than

$$L_{EM} \sim 10^{44} \text{erg/s} \quad (17)$$

at the distance D_{GZK}. This must be an extremely powerful source of TeV radiation. For comparison, the flux of the Crab nebula at energies above 15 TeV is $F_{Crab} \sim 10^{-11}$ erg/cm$^2 \cdot$ s [10]. Thus, the hypothetical «quiet» cosmic ray sources, which would explain the observed UHECR flux, should be 100–1000 times brighter in the TeV band than the Crab nebula.

The possibility of the existence of persistent point sources of this type in the Northern hemisphere is excluded by the measurements of the HEGRA AIROBICC Array [10] and by the MILAGRO experiment [11, 23]. The upper limit on the energy flux from an undetected point source of ~ 15 TeV γ-rays provided by HEGRA/AIROBICC group [10] is at the level of $F_{HEGRA} \lesssim (2\text{–}3)\, F_{Crab}$. Much tighter upper limit was published recently by the MILAGRO collaboration, $F_{MILAGRO} \lesssim (0.3\text{–}0.6)\, F_{Crab}$ [23].

7. DISCUSSION

The above model of particle acceleration near the horizon of a supermassive black hole is based on a number of assumptions: the maximum rotation moment of the black hole, a low matter and radiation density in the acceleration volume, the absence of back reaction of the accelerated particles and their radiation on the EM field, and the uniform magnetic field at large distance from the black hole. These assumptions have one common feature: they facilitate acceleration to higher energies and minimize losses (and, therefore, the produced radiation). We have found that even under these idealized conditions, the acceleration of protons to the energy $E = 10^{20}$ eV requires extreme values of parameters, $M \approx 10^{10} M_\odot$ and $B \approx 3 \cdot 10^4$ G. Moreover, the acceleration is very inefficient: the total power emitted in TeV gamma rays is 100–1000 times larger than in UHECR. In view of recent TeV observations, this rules out some UHECR models based on this acceleration mechanism, e.g., the model of several nearby dormant galactic nuclei («dead quasars»), which was aimed to explain the observed UHECR flux with energy $E > 10^{20}$ eV.

In a more realistic case, the above conditions may not be satisfied completely, and the acceleration of protons to energy $E \sim 10^{20}$ eV in the continuous regime may not be possible. The synchrotron losses due to the presence of a random component B_{rand} of the magnetic field can be neglected if

$$B_{rand} \ll \frac{B}{\mathcal{R}} \frac{m}{m_p} \approx 10^{-2} \frac{m}{m_p} B \, , \quad (18)$$

where $\mathcal{R}$ is given by (13). This means that the presence of a tiny (1% level) random magnetic field leads to a decrease of the maximum energies of accelerated protons and an increase of the electromagnetic luminosity of the accelerator. We note that the synchrotron radiation is emitted in this case at the energies

$$\epsilon_{synch} \le \frac{m}{e^2} \frac{B}{B_{rand}} \approx 0.1 \frac{m}{m_p} \frac{B}{B_{rand}} \text{ TeV} . \quad (19)$$

The power is still given by Eq. (14).

Even if the strength of the random component of the magnetic field is as small as $10^{-5}\, B$, for electrons, which are inevitably present in the accelerator, the synchrotron losses dominate over the curvature losses. The electromagnetic power emitted by electrons is then in the 100 MeV–10 TeV energy band (see Eq. (19). Assuming that the density of electrons is of the same order as the density of protons, we obtain the same estimate (14) for the 100 MeV luminosity of the accelerator. This means that such an accelerator is not only a powerful TeV source, but also an extremely powerful EGRET source.

Even if the idealized conditions are realized in Nature, the corresponding objects must be extremely rare. Thus, only a very small fraction of (active or quiet) galactic nuclei could be stationary sources of UHE protons with energies above 10^{20} eV.

If the parameters of the model are not precisely tuned to their optimal values, one expects the maximum energies of accelerated protons to be somewhat below 10^{20} eV. It is therefore interesting to note that most of the correlations of UHECR with the BL Lacertae objects come from the energy range $(4–5)\cdot 10^{19}$ eV. The central engine of BL Lacs is thought to consist of a supermassive black hole; it is possible that the acceleration mechanism considered above is operating in these objects[2)]. This mechanism may also operate in the centers of other galaxies that may have (super)massive black holes, including our own Galaxy, where it may be responsible for the production of cosmic rays of energies up to $\sim 10^{18}$ eV [13, 25].

The constraints from TeV observations are different in this case. First, cosmic rays of lower energies propagate over cosmological distances, and hence the UHECR flux is collected from a much larger volume, and the number of sources may be larger. Correspondingly, the TeV luminosity of each source is smaller. Second, the TeV radiation attenuates substantially over several hundred megaparsecs. Third, at $E < 10^{20}$ eV, the ratio L_{EM}/L_{UHECR} is smaller. For example, we consider the case of $O(100)$ sources located at $z \approx 0.1$ with a typical maximal energy at the accelerator $E \approx 5\cdot 10^{19}$ eV. According to Fig. 1, the typical energy of produced γ-rays is then ≈ 4 TeV. The flux of γ-rays in this energy range is attenuated by a factor 10–100, while according to Eq. (13), $L_{EM}/L_{UHECR} \approx 50$. Therefore, we may expect $F_{EM} \approx (0.01–0.1)\, F_{Crab}$ for the TeV flux from each of these sources. This is within the range of accessibility of modern telescopes. For example, the TeV flux from the nearby ($z = 0.047$) BL Lac 1ES 1959+650, which correlates with the arrival directions of UHECR [6, 26], is at the level of $0.06 F_{Crab}$ during quiet phase and rises up to $2.9 F_{Crab}$ during flares. Several other BL Lacs, which are confirmed TeV sources, have fluxes $\approx 0.03 F_{Crab}$, see, e.g., Ref. [27].

This paper mainly concerns the stationary regime of acceleration when the acceleration volume is not polluted by the creation of e^+e^- pairs. To ensure this condition, we required the magnetic field not to exceed the critical value (12). If the magnetic field is larger, the acceleration by the mechanism considered here can only occur during flares, which are interrupted by the creation of e^+e^- plasma and neutralization of the electric field as discussed at the end of Sec. 4. Although we do not have a quantitative model of a flare, some features of this regime and its consequences for the UHECR production can be understood qualitatively. Because there is no constraint on the magnetic field in this regime, the maximum energies of the accelerated protons may exceed 10^{20} eV. However, the efficiency of the acceleration during flares must be much lower than in the stationary case. First, as follows from Fig. 2, the ratio L_{EM}/L_{UHECR} is larger at large B. Second, the dominant part of the EM radiation is produced by the created electrons and positrons, whose number density by far exceeds the number density of protons. Thus, we expect that the ratio L_{EM}/L_{UHECR} for this sources is much larger than in Eq. (14).

An UHECR accelerators operating in the flaring regime would produce an approximately constant UHECR flux at the Earth. The reason is the time delay of protons due to random deflections in the extragalactic magnetic fields. This delay is of the order of $\sim 10^5[\alpha/1^\circ]^2$ yr for a source at 100 Mpc, where α is the deflection angle. Because the time scale of flares (light crossing time) is of the order of day(s), the variations of UHECR flux would disapper upon averaging. On the contrary, the TeV radiation from such a source would be highly variable, with powerful «TeV bursts» and the average energy flux in TeV band exceeding that in UHECR by a factor of 10^4 or higher. We note that there exist tight constraints on transient TeV sources: the energy flux of a TeV burst of duration 10^5 s has to be less than 10^{-10} erg/cm$^2\cdot$s $\sim 10\, F_{Crab}$ [11, 12]. As in the case of a stationary accelerator, this constraint excludes the possibility to explain the observed UHECR flux by a few nearby proton accelerators operating in the flaring regime. The hypothesis of several hundred remote sources is not constrained by TeV observations.

To summarize, the model of compact UHE proton accelerators that operate near the horizons of supermassive black holes in galactic nuclei can explain only the sub-GZK flux. A large number (several hundred) of sources situated at cosmological distances. Production of UHECR in such sources may be associated with the blazar-type activity, TeV γ-radiation being an important signature of the model, testable by the existing γ-ray telescopes.

2) We note that if the accelerated particles interact with the photon background outside the central engine, the same mechanism may be responsible for «photon jets» discussed in Ref. [24].

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