Extragalactic cosmic ray sources with very small particle flux on Earth and their study

A. V. Uryson[*]

P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow 119991, Russia

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The existence of extragalactic ultrahigh-energy cosmic ray sources giving a very small particle flux on the Earth is considered. While the majority of cosmic rays is emitted by a source class providing the flux observed on the Earth, this small part of the particle flux is assumed to be accelerated in an additional subclass of sources of cosmic rays. As an illustration of this subclass of sources, we discuss accretion disks around supermassive black holes where particles are accelerated by electric fields. Because of acceleration mechanism, particle injection spectra are assumed to be hard. In this case cosmic ray flux on the Earth is too low for detection. But propagating particles produce in space a noticeable flux of diffuse gamma ray emission and neutrinos. It should be accounted for when analyzing other source models and dark matter models. At energies $E > 10^{19}$ eV cascade neutrino spectra depends on cosmic ray injection spectra. It is proposed to study cosmic ray sources under consideration using data on gamma ray and neutrino emission along with cosmic ray data.

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I. INTRODUCTION

Cosmic rays (CRs) at ultrahigh energies (UHEs) —$E > 4 \times 10^{19}$ eV—seem to be accelerated in extragalactic pointlike sources, but still they are not revealed. Source identification by particle arrival directions was not effective mainly due to two reasons: errors in CR arrivals of $\sim 1°$ that are too large to select a source among astrophysical objects falling in the error box around arrival direction, and CR deflection in extragalactic magnetic fields which have been studied insufficiently to date.

Recently some characteristics of UHECR sources have been obtained exploring cosmological evolution of astrophysical objects where CRs seemingly can be accelerated to UHE, and varying values of injection spectral index a (injection spectra being $\propto E^{-a}$ [1–3]). As a result, evolution parameters of possible sources together with injection spectral indices have been determined that provide excellent fits to energy spectra measured at ground-based arrays the Pierre Auger Observatory (PAO) and the Telescope Array (TA).

More than a good fit to the spectra measured has been given in [1–3].

Since UHECRs propagating in space initiate electromagnetic cascades [4,5], they contribute to the extragalactic isotropic diffuse gamma ray background (IGRB). Therefore the intensity of cascade gamma ray emission $I_{\mathrm{cascade}\,\gamma}$ should satisfy the condition

$$I_{\mathrm{cascade}\,\gamma} < \mathrm{IGRB} - I_{\mathrm{unresolved\ sources}}, \qquad (1)$$

where $I_{\mathrm{unresolved\ sources}}$ is the intensity of individual unresolved gamma ray sources that is a part of IGRB. The intensity IGRB is measured by the gamma ray telescope Large Area Telescope (LAT) on board the cosmic observatory *Fermi* [6], and $I_{\mathrm{unresolved\ sources}}$ is estimated theoretically [7]. In [1–3] the intensity $I_{\mathrm{cascade}\,\gamma}$ has been calculated in models which fit the measured UHECR spectrum. In this way source parameters have been selected with which condition (1) is satisfied: injection proton spectral index equal to $a = 2.1$, 2.2, 2.6 [2], depending on the cosmological evolution of possible sources.

A further step toward the revealing of UHECR sources was taken in [8], where a minimal model is suggested using a single source class and describing in a unified way not only CR spectra and the CR contribution to IGRB but also the astrophysical neutrino flux from the neutrino observatory IceCube [9] along with the data on the CR composition from the PAO (mean shower maximum depth and its width [10]). (In the model [8] the CR composition and the CR flux are described in the whole energy range above 10^{17} eV. The behavior of intensity and the spectral shape of high-energy gamma rays and neutrinos were discussed in [11].)

Here we consider a possible subclass of UHECR sources with injection spectra $\propto E^{-a}$ harder than those above. Inspired by [12], we suppose that hard spectra can be formed when particles are accelerated by electric fields in accretion disks around supermassive black holes (SMBHs).

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[*] uryson@gmail.com

The spectral indices above are typical for particle acceleration on shock fronts [13], which can occur, for example, in active galactic nucleus (AGN) jets (see, e.g., [14]).

Computing CR fluxes and cascade gamma ray emission, we show that UHECR sources with hard injection spectra give negligible particle fluxes near the Earth, but CRs produce a noticeable diffuse gamma ray flux in intergalactic space satisfying condition (1).

Neutrino fluxes are also generated during UHECR propagation. That is why one more condition on CR models arises: cascade neutrino intensity $I_{\mathrm{cascade}\,\nu}$ should be less than the intensity of the astrophysics neutrino measured ($I_{\nu\,\mathrm{measured}}$),

$$I_{\mathrm{cascade}\,\nu} < I_{\nu\,\mathrm{measured}}. \tag{2}$$

Neutrino flux is obtained, as mentioned above, at the neutrino observatory IceCube, and also at the PAO.

At IceCube the cosmic neutrino flux has been measured in the energy range of about $(10^6\text{–}10^{11})$ GeV [9]. At the PAO the tau-neutrino flux is obtained in the range of approximately $(10^{17}\text{–}10^{20})$ eV [15]. In the model suggested, cascade neutrino intensity satisfies condition (2), both at the IceCube observatory and in the PAO energy range.

Thus we conclude that possibly extragalactic UHECR sources exist giving insignificant CR flux on the Earth. Characteristics of these sources can be studied measuring extragalactic diffuse gamma ray and neutrino background together with the UHECR data.

The computations of particle propagation in the space were performed with the TRANSPORTCR code [16].

II. THE MODEL

We assume that UHECRs are accelerated in SMBHs, the maximal particle energy $E_{\max}$ depending linearly on SMBH mass M [12]: $E_{\max} = 10^{20}$, 4×10^{20}, 4×10^{21} eV, for $M = 2.5\times10^6\ M_\odot$, $10^7\ M_\odot$, $10^8\ M_\odot$, respectively, where $M_\odot$ is the solar mass. We consider SMBHs with these masses with the ratio $2.5\times10^6\ M_\odot : 10^7\ M_\odot : 10^8\ M_\odot = 0.313 : 0.432 : 0.254$ derived from the local SMBH function [17]. The fraction of SMBHs with masses larger than $10^8\ M_\odot$ is small compared to the values above [17]. SMBHs with masses smaller than $2.5\times10^6\ M_\odot$ produce CRs at energies less than 10^{20} eV, and their cascade emission is much lower than that of CRs at higher energies [18]. Thus CRs from SMBHs with masses lower than $2.5\times10^6\ M_\odot$ and higher than $10^8\ M_\odot$ are not accounted for.

The SMBH evolution is unclear, and therefore we consider the evolution scenario ([19]; see also [16]) of powerful active galactic nuclei—blue Lacertae objects.

The injection spectra in sources assumed to be exponential, $\propto E^{-a}$, with a spectral index equal to $a = 2.2$, 1.8, 1, 0.5, 0, where 0 corresponds to equiprobable generation of particles at any UHE.

We assume that UHECRs consist of protons.

Protons lose energy in synchrotron and curvature radiation in magnetic fields in their path from acceleration region. The problem of energy losses of escaping CRs is discussed in [14]: approximately 0.4% of accelerated CRs flies away, losing insignificant part of their energy.

In intergalactic space UHECRs interact with microwave and radio emissions mainly in reactions $p + \gamma_{\mathrm{rel}} \to p + \pi^0$, $p + \gamma_{\mathrm{rel}} \to n + \pi^+$. Pions decay, $\pi^0 \to \gamma + \gamma$, $\pi^+ \to \mu^+ + \nu_\mu$, giving rise to gamma quanta and muons, and muons decay, $\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$, giving rise to positrons and neutrinos. Gamma quanta and positrons generate electromagnetic cascades in the reactions with cosmic microwave emission and extragalactic background light: $\gamma + \gamma_b \to e^+ + e^-$ (pair production) and $e + \gamma_b \to e' + \gamma'$ (inverse Compton effect).

The extragalactic background emissions are considered as follows. The cosmic microwave background radiation has Planck energy distribution with the mean value $\eta_r = 6.7\times10^{-4}$ eV. The mean photon density is $n_r = 400\ \mathrm{cm}^{-3}$. The extragalactic background light characteristics are taken from [20]. To describe the background radio emission, we use the model of the luminosity evolution for radio galaxies [21].

Magnetic fields in intergalactic space influence cascades due to electron synchrotron emission. With the fields being of $10^{-9}\text{–}10^{-8}$ G or lower, the cascade electrons lose energy insignificantly [22]. Though the magnetic field in intergalactic space is apparently nonuniform [23–25], we suppose that regions with fields higher than the above seemingly occupy a small part of extragalactic space, so extragalactic magnetic fields do not break cascades.

In these assumptions spectra of protons, gamma rays, and neutrinos near the Earth were calculated with the TRANSPORTCR code [17].

III. RESULTS

The calculated UHECR energy spectra along with the spectra obtained by the PAO [26] and the TA [27] are shown in Fig. 1. The model spectra are normalized to the PAO spectrum at an energy of $10^{19.5}$ eV (3.16×10^{19} eV). The model CR spectra are lower than the spectra measured by several orders of magnitude (except for the point of normalization and the point of about $10^{19.45}$ eV). In addition, the calculated spectra differ greatly in shape from the spectra measured. In the model CRs at energies of about 4×10^{21} eV fall on the Earth, but their flux is too low to be detected.

We proceed now to the intensity of gamma ray emission that UHECRs initiate in extragalactic space.

Spectra of the cascade gamma ray emission are virtually independent on the initial CR spectrum [25,28], and here we analyze only the intensity of the cascade emission without discussing the spectra. Namely, we compare model

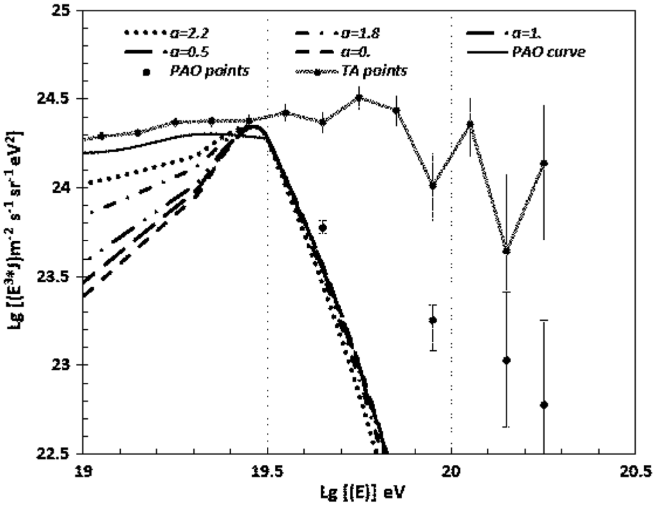

FIG. 1. UHECR energy spectra measured on the PAO and the TA, and UHECR spectra on the Earth calculated for injection spectra with various spectral indices a (see the legend). Model spectra are normalized to the PAO data at an energy of $10^{19.5}$ eV (3.16×10^{19} eV).

integral intensity of the cascade emission with the *Fermi* LAT data in the range $E > 50$ GeV (as was done in [2]). The reason is that in this range the contribution of discrete unresolved gamma ray sources is estimated in [7].

The integral intensity of the cascade emission $I_{\mathrm{cascade}\,\gamma}(E > 50\ \mathrm{GeV})$ is found from the differential intensity, which is calculated with the TransportCR code. For the set of spectral index values $a = 2.2$, 1.8, 1, 0.5, 0, the cascade integral intensity is $I_{\mathrm{cascade}\,\gamma}(E > 50\ \mathrm{GeV}) \approx (1.1\text{–}1.6) \times 10^{-10}\ (\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1})$.

Now we will compare the model intensity of the cascade gamma ray emission with the *Fermi* LAT data. Extragalactic IGRB measured by the *Fermi* LAT is [6]

$$\mathrm{IGRB}(E > 50\,\mathrm{GeV}) = 1.325 \times 10^{-9}\ (\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}). \qquad (3)$$

This value includes the emission from individual unresolved gamma ray sources. Their contribution to the IGRB at energies $E > 50$ GeV is equal to $86(-14, +16)\%$ [7]. Subtracting from the IGRB the unresolved source contribution of 86%, we obtain

$$\mathrm{IGRB}_{\text{without unresolved sources}}(E > 50\ \mathrm{GeV}) = 1.855 \times 10^{-9}\ (\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}). \qquad (4)$$

The model cascade gamma ray emission $I_{\mathrm{cascade}\,\gamma}(E > 50\ \mathrm{GeV})$ is less than the value (4) for all spectral indices considered, contributing to the $\mathrm{IGRB}_{\text{without unresolved sources}}$ $(E > 50\ \mathrm{GeV})$ about 10%. Thus the model under consideration satisfies condition (1).

Neutrinos are also generated during UHECR propagation, whereupon condition (2) on the CR models arises. Model neutrino fluxes together with those measured at IceCube [9] and at the PAO [15] are shown in Fig. 2, with the neutrino flux from IceCube being the strongest limitation. Calculated fluxes are lower than measured ones, so our model satisfies condition (2).

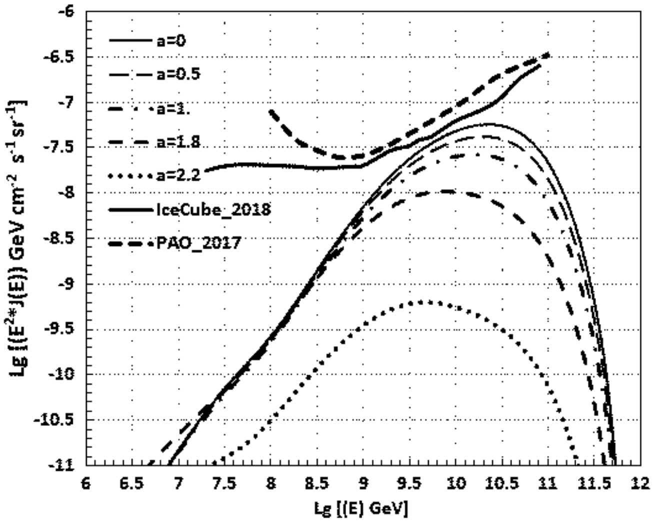

FIG. 2. Model spectra of cascade neutrinos on the Earth calculated for UHECR injection spectra with various spectral indices a (see the legend), the astrophysical neutrino flux from IceCube [9] (labeled "IceCube_2018"), and the upper limit on the diffuse flux of tau neutrinos from the PAO [15] (labeled "PAO_2017").

Figure 2 shows that the cascade neutrino spectrum at energies $E > 10^{19}$ eV depends on the injection CR spectrum. This energy range is available for measurement. Thus it is possible to apply neutrino data for analyzing the model under consideration.

IV. DISCUSSION

Sources considered in the model obey constraints arising from the gamma ray and neutrino fluxes measured. At the same time these sources contribute negligibly to the CR flux on the Earth. Thus other sources provide the majority of UHECRs, which in turn generate cascade gamma rays and neutrinos when they propagate in space. Now we consider whether our model is consistent with the minimal model [8], describing the UHECR majority, i.e., data on CRs together with cosmic background emission.

In our model cascade gamma rays contribute about 8%–12% to the diffuse isotropic gamma ray emission from the *Fermi* LAT. Thus the model leaves room for gamma rays initiated by the UHECR majority.

Neutrino fluxes in the model are also lower than those measured. However, in the energy range $10^{18.7}$–10^{19} eV protons with injection spectral indices $a = 0$, 0.5 produce neutrino fluxes which evidently do not leave enough room for the neutrinos obtained in [8].

The intensity of secondary gamma rays and neutrinos in Fig. 2 has been obtained by normalizing the model CR flux to PAO data at $10^{19.5}$ eV. Normalization of CR fluxes at an energy of approximately $10^{19.45}$ eV reduces them by $\approx 20\%$. Then model fluxes of cascade gamma rays and neutrinos also decreases: in the range $10^{18.7}$–10^{19} eV the model neutrino flux makes up $\approx 70\%$ of the flux from IceCube at $a = 0$, and $\approx 50\%$ at $a = 0.5$. This is also apparently too high to be consistent with the minimal model [8]. Therefore we conclude that proton injection spectra with indices $a = 0$, 0.5 are formed with lower efficiency than suggested by our model, or excluded. Proton injection spectra with indices $a > 0.5$ are consistent with the minimal model [8].

The normalization above satisfies the only condition: the model particle flux does not exceed the measured one. But it is unknown how much less it can be. Because of this, gamma ray and neutrino fluxes obtained in the model are the upper limits for cascade emission.

In the model we do not account for proton interactions with IR photons and gas in the gas-dust torus surrounding the central part of the AGN. Accounting for particle interactions in the torus, production of secondary gamma rays and neutrinos increases somewhat [8].

V. CONCLUSION

Possibly extragalactic UHECR sources with hard injection spectra $\propto E^{-a}$, $a \leq 2.2$ exist. Hard spectra can be formed, for instance, when particles are accelerated by electric fields in SMBH accretion disks, with the maximal particle energy depending on the SMBH mass. This acceleration process was analyzed in [12].

We consider SMBHs with masses $M = 2.5 \times 10^6\ M_\odot$, $10^7\ M_\odot$, $10^8\ M_\odot$. The fraction of SMBHs with larger masses is much less [17]. SMBHs with smaller masses produce CRs at energies less than 10^{20} eV, and their cascade emission is much lower than that of CRs at higher energies [18]. So CRs from them are not accounted for.

Thus any AGN containing the SMBH with a mass above can be a hard UHECR source.

On the Earth the UHECR flux from sources discussed is too low for detection even with giant ground-based arrays. But these UHECRs produce in the space noticeable fluxes of diffuse gamma rays and neutrinos, which satisfy conditions arising from diffuse gamma ray and neutrino fluxes measured by the *Fermi* LAT [7] and IceCube [9].

At the same time the majority of UHECRs are accelerated by other sources or processes, and these UHECRs generate in turn cascade gamma rays and neutrinos when they propagate in space. The suggested subclass of sources leaves room for the model emission obtained in the minimal model [8], describing the data on CRs together with cosmic background emission.

The way to investigate the suggested subclass of sources is to study extragalactic diffuse gamma ray and neutrino emission.

Analyzing diffuse gamma ray emission, the contribution from individual unresolved gamma ray sources should be extracted. At present the latter is determined with a large percentage error of about 15% [7]. To improve it, gamma ray telescopes with better angular resolution than that of the *Fermi* LAT (0.05° at energies above 100 GeV) are required. A comparison of parameters of current and planned gamma telescopes is presented in [29]. Currently the gamma ray telescope MAST proposed in [29] has the best characteristics at energies above 20 GeV: depending on the energy, its angular resolution is 3–10 times higher than that of the *Fermi* LAT. The gamma ray telescope GAMMA-400 is also suitable, as its angular resolution is approximately 0.01–0.02° at an energy of 100 GeV. It is planned for launch in 2025 [30].

Future neutrino observatories with parameters better than those of IceCube are listed and discussed in [9] and the references therein.

More than the study of hard UHECR sources considered is of interest. The contribution to the diffuse gamma ray and neutrino emission by UHECRs discussed should be accounted for when analyzing cascade emission in any other source models. Also the additional part of diffuse gamma ray emission should be taken into account when analyzing dark matter models.

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