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Extragalactic Diffuse Cascade Emission as a Probe of Processes in Active Galactic Nuclei

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Abstract: In this study, we discuss possible imprint of source characteristics on extragalactic diffuse cascade emission that is initiated by ultra-high energy cosmic rays propagating through the universe. The common opinion is that cosmic ray sources are active galactic nuclei. Based on cascade emission analyses we demonstrate that possibly a new subclass of cosmic ray sources exists, a particle flux from which on the Earth is small, however producing noticeable gamma-ray and neutrino emissions in the universe. We also estimate a fraction of active galactic nuclei with super-strong magnetic fields in their centers among those with common characteristics.

Keywords: Cosmic Rays, Gamma-Ray Emission, Active Galactic Nuclei, Supermassive Black Holes

Introduction

At present common opinion is that Cosmic Rays (CR) at Ultra-High Energies (UHE) have extragalactic origin, their sources being point-like objects, namely Active Galactic Nuclei (AGN). The cause of AGN activity is Supermassive Black Holes (SMBH), located in the AGN central part. CRs are accelerated in the SMBH vicinity.

CR is detected by giant ground-based arrays providing the following data: Particle arrival directions, CR energy spectra and elemental composition. It may seem that CR arrival directions are pointers to sources. However, it is not so as charged particles deflect in intergalactic magnetic fields, its structure being studied insufficiently to derive particle trajectories and find objects emitted by CRs.

Both CR energy spectra and elemental composition change during particle propagation in intergalactic space. The reason is CR interaction with the Cosmic Microwave Background (CMB), radio background and Extragalactic Background Light (EBL).

Interaction with CMB results in GZK-effect (Greisen, 1966; Zatsepin and Kuzmin, 1966). Space distribution of CR sources along with source models are studied using GZK-effect. Assuming CRs at energies higher than $4{\cdot}10^{19}$ eV to be protons they interact with CMB (and radio background) via reactions $p + \gamma_{background} \rightarrow p + \pi^0$, $p + \gamma_{background} \rightarrow n + \pi^+$. Decays $\pi^0 \rightarrow \gamma + \gamma$, $\pi^+ \rightarrow \mu^+ + \nu_\mu$ give rise to gamma quanta and muons. Muons decay $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$ giving rise to positrons and neutrinos. CRs at energies of about 10^{18} eV interact with the background through reaction $p + \gamma_{background} \rightarrow p + e^+ + e^-$.

Gamma-quanta and positrons generate electromagnetic cascades interacting with CMB and EBL: $\gamma + \gamma_b \rightarrow e^+ + e^-$ (pair production) and $e + \gamma_b \rightarrow e' + \gamma'$ (inverse Compton effect) (Hayakawa, 1966; Prilutsky and Rozental, 1970).

Cascade gamma-ray and neutrino fluxes are used in source investigation along with CR particle spectra. The fermi Large Area Telescope (LAT) onboard the gamma-ray space observatory fermi provides data on gamma-ray emission and data on neutrino emission are obtained by the neutrino observatory icecube and the giant ground-based array Pierre Auger Observatory (PAO). At present the joint analysis of CR data along with gamma-ray and neutrino emissions is used in studying UHE CR source models (Giacinti *et al*., 2015; Gavish and Eichler, 2016; Kachelrieß *et al*., 2017).

We performed such joint analysis to study CR acceleration near SMBHs in Uryson (2019). CR can be accelerated in various processes, injection spectra depending on them. In this study we consider two models with various particle spectra, using the ideas and results of (Haswell *et al*., 1992; Kardashev, 1995), which are the following.

In the paper by Haswell *et al*. (1992), accretion disks around SMBH are examined for electric fields and particle acceleration in these fields is discussed. Using the results of (Haswell *et al*., 1992), model I is proposed in which CR injection spectra are hard, namely injection spectra being $\propto E^{-a}$, a ≤ 2.2.

In the paper by Kardashev (1995), a super strong magnetic field of ~10^{11} G can possibly exist around SMBH. This is argued by observational data (Zakharov *et al*., 2003). This super strong magnetic field induces an electric field and it is not compensated by plasma charged particles in some

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regions of the SMBH magnetosphere. The electric field accelerates particles to UHE. According to this idea, we propose model II with monoenergetic CR injection spectra.

In our paper, we consider UHE CR sources with redshifts up to z = 5.5. CR sources being remote it is necessary to account for their evolution. The SMBH evolution being unclear, we apply the evolution scenario of powerful AGNs, namely of Blue Lacertae objects (BL) Lac (Giacinti *et al*., 2015; Hillas, 1984). In model II we consider also an evolution scenario as in radio galaxies (Smolčić *et al*., 2017). In this case, we apply the evolution of the density of objects, because the luminosity-redshift correlation for radio galaxies is unclear.

In this study, extragalactic background emission-CMB, EBL and radio emission, are considered in the following way. The CMB has a Planck energy distribution with the mean value $\varepsilon_r = 6.7\cdot10^{-4}$ eV, the mean photon density being $n_r = 400$ cm^{-3}. The characteristics of EBL are taken from (Inoue *et al*., 2013). Describing the background radio emission we use the results (Protheroe and Biermann, 1996) where the model of the luminosity evolution for radio galaxies is suggested.

There are magnetic fields in intergalactic space and cascade electrons lose energy generating synchrotron emission. Synchrotron energy losses are minor in fields of 10^{-9} G and lower (Uryson 1998). The intergalactic magnetic field seems to be nonuniform (Wielebinski and Beck, 2005; Dolag *et al*., 2005; Khalikov and Dzhatdoev, 2021) and ref in. We suppose that fields higher than 10^{-9} G occupy a small part of intergalactic space and therefore do not take into account their influence on cascades.

Giant ground-based arrays studying UHECRs are the PAO and the Telescope Array (TA). Both arrays reported that CR composition was mixed with Helium and heavier nuclei up to Ferrum (Aab *et al*., 2020; Abbasi *et al*., 2018). Yet in this study, we assume that UHE CRs consist of protons.

In this study following parameters of UHE CR sources are varied: Injection spectra, whose shape depends on processes of particle acceleration and evolution of UHE CR sources. Extragalactic cascade emission bears an imprint of these parameters, allowing us to obtain the results below.

A new type of UHECR source possibly exists, contributing to the particle flux on Earth insignificantly, but providing not-so-small fluxes of gamma-rays and neutrinos which are generated by CRs in electromagnetic cascades in intergalactic space. Therefore studying sources of this type can be fulfilled by measuring the extragalactic diffuse gamma-ray and neutrino background.

In addition, in model II, we derive the relative number of ‘exotic’ objects-SMBHs which are surrounded by super strong magnetic fields.

The computations of particle propagation in space were fulfilled with the code transport CR (Kalashev and Kido, 2015), which is publicly available.

Models

Now we discuss in detail model assumptions of particle acceleration UHE in AGNs, energy-consuming processes take place due to the SMBH action in the galactic center. First, we discuss model I based on results by Haswell *et al*. (1992). Haswell *et al*. (1992) electric fields in the accretion disc can accelerate particles up to UHE. Due to the field structure, the maximal particle energy $E_{\max}$ depends linearly on SMBH mass M. For $M = 2.5\cdot10^6 M_\Theta$, $10^7 i_\Theta$, $10^8 M_\Theta$, where M_Θ is the solar mass, the maximum particle energies are $E_{\max} = 10^{20}$, $4\cdot10^{20}$, $4\cdot10^{21}$ eV, respectively (Haswell *et al*., 1992). The local SMBH function is given in Mutlu-Pakdil *et al*. (2016), in accordance with which the masses above are distributed with the ratio $2.5\times10^6 M_\Theta$: $10^7 M_\Theta$: $10^8 M_\Theta$ = 0.313:0.432:0.254. We do not account for CRs from SMBHs with higher and lower masses, because their fraction is smaller than those above (Mutlu-Pakdil *et al*., 2016).

In model I we adopt that injection spectra are power-law, $\propto E^{-\alpha}$ and the acceleration mechanism suggested by by Haswell *et al*. (1992) can produce hard spectra with the values of the spectral index a = 2.2, 1.8, 1, 0.5, 0, (which is harder than spectra used e.g., by Kachelrieß *et al*. (2017), where the main class of possible UHE CR sources is considered.) Using the index value 0 we analyze generation of an equal number of particles at any UHE.

Second, in model II we analyze the idea by Kardashev (1995), where SMBH is surrounded by a super strong magnetic field, that induces the electric field near a SMBH in which charged particles are accelerated up to 10^{21} eV. Then the CR injection spectrum is monoenergetic, with the energy $E = 10^{21}$ eV. This spectrum is adopted in model II.

Other model characteristics evolution, parameters of background emissions and CR elemental composition are listed in the introduction.

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Results

Calculated and measured UHE CR energy spectra are shown in Fig. 1 taken from (Uryson, 2019): Spectra calculated in model I along with the spectra measured by the PAO and the TA (Aab *et al*., 2017; Verzi *et al*., 2017) are shown in Fig. 1a, spectra obtained in model II along the fit of PAO spectrum from (Verzi *et al*., 2017) are shown in Fig. 1b. The calculated spectra are normalized to the spectrum obtained by the PAO at the energy of $10^{19.5}$ eV ($3.16 \cdot 10^{19}$ eV). Both calculated spectra in Fig. 1 are lower than the spectra measured and the difference is of several orders of magnitude (except the point of normalization and the point of about $10^{19.45}$ eV). Moreover, the model and measured spectra differ in shape noticeably. So in both models, the UHECR flux is too low to be detected.

Now we discuss the results of cascade gamma-ray emission and compare them with fermi-LAT data.

Fermi LAT measures the extragalactic Isotropic diffuse Gamma-Ray Background (IGRB) (Ackermann *et al*., 2015). It has several components, two of which are: The cascade emission $I_{cascade\gamma}$ and the intensity of individual unresolved gamma-ray sources $I_{unresolvedblazars}$. As $I_{cascade\gamma}$+ $I_{unresolved\ \mathrm{blazars}}$<IGRB, the intensity of cascade gamma-ray emission $I_{\mathrm{cascade}\gamma}$ should be:

$$I_{cascade\gamma} < IGRB - L_{unresolvedblazars} \quad (1)$$

The procedure of comparison is presented in detail in Uryson (2019). The results of the comparison are the following. Condition (1) is satisfied in the model I. In model II the intensity of the cascade emission $I_{cascade\gamma}$ is higher than (IGRB-$I_{unresolved\ blazars}$).

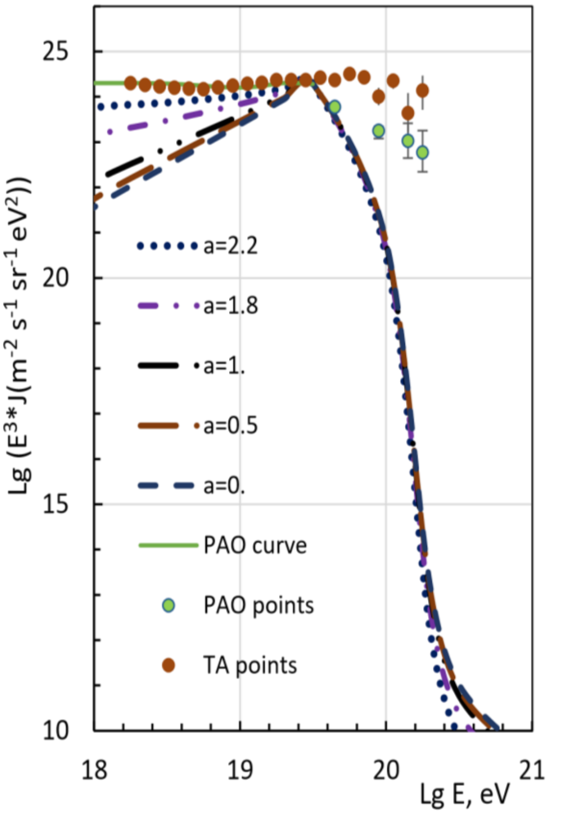

Fig. 1a: CR spectra measured on the PAO (Aab *et al*., 2017) and the TA (Verzi *et al*., 2017) along with those calculated using injection spectra with various spectral indices (see the legend)

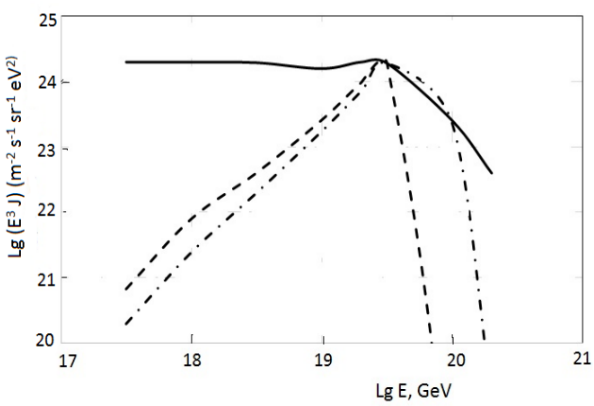

Fig. 1b: UHECR energy spectra: Solid line - the fit of the PAO UHECR energy spectrum from (Verzi *et al*., 2017), dashed line model spectrum calculated for the evolution of sources as in radio galaxies, dash-dotted line-the model spectrum calculated for the evolution of sources as in BL Lac objects. The model spectra are normalized to the PAO spectrum at the energy of $10^{19.5}$ eV

However, in model II the CR sources are ‘exotic’, therefore they are rare and their total CR flux is definitely smaller. Thus UHE CRs from these sources provide lower cascade emission $I_{\text{cascade}\gamma}$ than the majority of UHE CRs. From these results, we now derive fraction R of the ‘exotic’ CR sources among BL Lac objects and radio galaxies. To do it we calculate the part of 'exotic' sources which provide cascade emission satisfying (1). The result is:

$$R < 18\% \textit{ comparing with BL Lac objects} \qquad (2)$$

$$R < 11\% \textit{ comparing with radio galaxies} \qquad (3)$$

Neutrino fluxes are produced as well during UHECR propagation. Another condition on CR models arises when analyzing neutrino fluxes: The cascade neutrino intensity $I_{cascade\upsilon}$ should be less than the intensity of astrophysics neutrino measured $I_{\upsilon\text{ measured}}$:

$$I_{cascade\upsilon} < I_{\upsilon measured} \qquad (4)$$

The neutrino flux is measured at the neutrino observatory IceCube in the energy range of about ($100\text{-}3\cdot10^6$) GeV (Aartsen *et al*., 2018) and at the PAO at energies ($2\cdot10^8$ -$2\cdot10^{10}$) GeV (Zas *et al*., 2017).

It appears that model I with injection spectrum indices a >0.5 satisfies (4). Proton injection spectra with indices a = 0, 0.5 result in cascade neutrino fluxes higher than (4). So such spectra are formed with a lower efficiency than it is assumed in model I, or they are not realized at all. This is discussed in detail in Uryson (2018). Accounting for (4) in model II, the values of R in (2) and (3) are reduced.

Discussion

We analyze models I and II in which CR sources contribute negligibly to the CR flux on Earth. Thus, other sources provide the majority of UHE CRs, which also generate electromagnetic cascades.

The majority of UHE CR sources are described e.g., in the minimal model by Kachelrieß *et al*. (2017), which satisfies both data on CRs and on extragalactic IGRB. Now we discuss if our models are consistent with the minimal model.

In model I, cascade gamma-ray contribution to the IGRB measured is approximately of 8-12%. It leaves room for gamma rays initiated by the UHECR majority. So, the model I is consistent with (Kachelrieß *et al*., 2017). Analyzing model II of ‘exotic’ SMBHs surrounded by a super strong magnetic field, we estimate their fraction which provides room for the UHECR flux from the main sources.

In models I and II, the calculated proton spectra are normalized to satisfy the condition: The model particle flux is less than the measured one. But it is unknown how much less can it be. Thus, the gamma-ray and neutrino fluxes obtained are upper limits for cascade emission.

The central part of an AGN is surrounded by the gas-dust torus. Proton interactions with IR photons and gas in the torus result in larger production of secondary gamma rays and neutrinos (Kachelrieß *et al*., 2017). In our paper, we do not consider this effect.

Details of a comparison between model results and fermi-LAT data are presented in Uryson (2018; 2019).

Gamma-ray telescopes with improved parameters are required for further studies of cascade emission, which is discussed in detail in Uryson (2018). The parameters of current and planned gamma-telescopes are listed and compared in (Dzhatdoev and Podlesnyi, 2019). Neutrino observatories with improved parameters are suggested as well. They are discussed in Zas *et al*. (2017) and references therein.

Conclusion

In this study, we show how studying extragalactic electromagnetic cascades can be used to investigate UHE CR sources. Assuming UHE CR sources to be SMBHs in central parts of AGNs we analyze initial CR spectra with various shapes formed in different processes of particle acceleration. Two models of CR acceleration in sources were studied.

In model I CRs are accelerated in accretion discs and particle maximal particle energy $E_{\max}$ depends linearly on SMBH mass, according to Haswell *et al*. (1992). CR injection spectra $\propto E^{-\alpha}$, where the spectral index a = 2.2, 1.8, 1, 0.5, 0; 0 corresponds to the equiprobable generation of particles at any UHE.

In model II the CR injection spectrum is monoenergetic, with a particle energy of 10^{21} eV. This spectrum can be realized when SMBHs exist having a super strong magnetic field and particles are accelerated in an induced electric field (Kardashev, 1995).

In both models, we analyze extragalactic electromagnetic cascades arising when UHE CRs propagate in space. The result is that possibly a type of extragalactic UHE CR source exists, giving a low CR flux on Earth. It is so low that cannot be detected with giant ground-based arrays available. However, these UHE CRs produce in space cascade gamma rays and neutrinos whose fluxes are not small. At present, the only way to investigate this subclass of sources is to study extragalactic diffuse gamma-ray and neutrino emissions.

In addition, we estimate the fraction of 'exotic' SMBHs surrounded with super-strong magnetic fields.

These results are obtained from varying parameters of UHE CR sources: Injection spectra, whose shape depends on processes of particle acceleration and evolution of UHE CR sources. Extragalactic cascade emission bears an imprint of these parameters and thus is used to investigate processes in the SMBH vicinity.

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Ethics

This article is original and contains unpublished material. The corresponding author confirms that all of the other authors have read and approved the manuscript and no ethical issues involved.

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