Constraints on ultra-high energy neutrinos from optically thick astrophysical accelerators

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Abstract

The Z-burst mechanism invoked to explain ultra-high energy cosmic rays is severely constrained by measurements of the cosmic gamma-ray background by EGRET. We discuss the case of optically thick sources and show that jets and hot spots of active galaxies cannot provide the optical depth required to suppress the photon flux. Other extragalactic accelerators (AGN cores and sites of gamma ray bursts), if they are optically thick, could be tested by future measurements of the secondary neutrino flux.

1 Introduction

Recent observational data on ultra-high energy (UHE, $E \gtrsim 10^{19}$ eV) cosmic rays give a significant evidence for clustering in their arrival directions [1]. This fact suggests that the observed extensive air showers are caused by particles created by point-like sources. Recently [2] correlations of the arrival directions of cosmic rays with BL Lac type objects – certain active galaxies located at cosmological distances – were found (for earlier discussion see Ref. [3]). Taken seriously, these data suggest that there exist particles which can travel for cosmological distances unattenuated (without significant energy loss).

Among the Standard Model particles, only neutrinos can propagate through the Universe unattenuated at ultra-high energy. However, neutrino primaries are excluded by reconstruction of atmospheric shower development [4, 5]. One of the ways out is to explore the so-called “Z-burst” mechanism [6] which works as follows. The Hot Big Bang cosmology predicts the existence of cosmic relic neutrino background. Ultra-high energy neutrinos interact with these background neutrinos very weakly, unless the energy is fine tuned to the resonance [7] with Z boson production in the s-channel, that is,

\[ E_{\text{res}} \approx \frac{4 \text{ eV}}{m_\nu} \cdot 10^{21} \text{ eV}, \]

for the conventional cosmological model.\textsuperscript{1} On resonance, the interaction cross section increases significantly. If the resonant scattering takes place within $\sim 50$ Mpc from the Earth,

\textsuperscript{1}Note that recently obtained limits on neutrino mass [8] suggest $m_\nu \lesssim 1$ eV.
then secondary protons and photons produced in decays of virtual $Z$ bosons can serve as primaries of the extensive air showers.

In astrophysical accelerators, the neutrino production is usually dominated by the two channels, namely, $p\gamma$ and $pp$ collisions, where one proton has extremely high energy. If the collision energy in the center-of-mass frame $E_{\text{cm}} \gg 1$ GeV, the total cross section is saturated by multipion production and UHE neutrinos emerge mostly as the products of charged pion decays. For $p\gamma$ processes the collision energy in the center-of-mass frame may be smaller, $E_{\text{cm}} \sim 1$ GeV, if UHE protons scatter off background soft photons ($E_{\gamma} \lesssim 10^{-2}$ eV). In this case the cross section is saturated by production of hadronic resonances (particular type of the resonance depends on the energy in the center-of-mass frame). These resonances decay into pions, protons and neutrons. Then UHE neutrinos appear as products of charged pion and neutron decays.

The generic feature of this mechanism is that it produces a certain amount of protons and photons per each neutrino. This may lead to contradiction with the observed fluxes if these particles leave the source. In the case of nucleons this statement is known as the Waxman-Bahcall bound [9] (see also Ref. [10]): the charged cosmic ray (CR) flux above $3 \cdot 10^{18}$ eV is measured with relatively good accuracy and implies that the sources have to be opaque for UHE nucleons.

A similar situation takes place for UHE photons which escape from the source. In the intergalactic space, the UHE photons give rise to electromagnetic cascade transferring energy into less energetic photons which propagate without attenuation [11]. The measurements of the flux of photons with $3 \cdot 10^{7}$ eV < $E_{\gamma} < 10^{11}$ eV by EGRET [12] constrains UHE neutrino flux in a similar way as the measurement of the charged CR flux [13]. Though a detailed study of the propagation should take into account a number of processes and numerical simulations are required (see, e.g., Ref. [14]), even simple order-of-magnitude estimates demonstrate that the most part of the primary photon energy flux transfers to the EGRET energies.

A few ways were suggested which could help to overcome the EGRET limits (recent discussions on these issues can be found, for instance, in Refs. [15, 16, 17]). One option is that the sources are more abundant at distances closer to the Earth which, in average, results in less energy losses [15]. Alternatively, one may assume that sources are optically thick for photons as well as nucleons, and only neutrinos escape. In this paper we analyze the latter possibility.

## 2 Optically thick part of the source

Let us estimate the mass required to make the source optically thick for photons. Denote the size of the absorption region (“damper”) along the photon flux by $l_\parallel$ and the size in the transverse direction by $l_\perp$. Let us consider first the energy loss by UHE photons due to their interaction with protons. Optical thickness requires that the size of the source is larger than the photon mean free path. This condition can be written as

$$n_p > \frac{1}{\sigma_{\gamma p} l_\parallel} \simeq 3 \cdot 10^5 \left(\frac{1 \text{ mb}}{\sigma_{\gamma p}}\right) \left(\frac{1 \text{kpc}}{l_\parallel}\right) \text{ cm}^{-3},$$

(2)
where $n_p$ is the proton number density in the damper and $\sigma_{\gamma p}$ is the total cross section of UHE photons on non-relativistic baryons. This cross section may be estimated by extrapolating the low energy data [18] as $\sigma_{\gamma p} \sim 1\text{ mb}$. We are interested in the highest-energy photons, $E_\gamma \gtrsim E_{\text{res}}$. Since $\sigma_{\gamma p}$ grows with energy, even larger proton density is required to suppress less energetic photons, $E_\gamma < E_{\text{res}}$, if they are present in the spectrum.

From Eq. (2) one finds the total mass of the absorption region,

$$M_d \sim m_p n_p l_\bot^2 l_\| > m_p \frac{l_\|^2}{\sigma_{\gamma p}} \simeq 10^{13} M_\odot \left( \frac{l_\bot}{1\text{ kpc}} \right)^2 \left( \frac{1\text{ mb}}{\sigma_{\gamma p}} \right).$$  

(3)

Inequalities (2) and (3) actually underestimate the proton density and the total mass of the absorption region. The reason is that after each $\gamma p$ interaction, approximately one third of the original photon energy flux is transferred into neutral pions and, upon their subsequent decay, into photons. Moreover, electrons and positrons from charged pion decays carry $1/6$ part of the original photon energy flux. Since strong magnetic fields are usually present in astrophysical accelerators, these electrons and positrons lose rapidly their energy into synchrotron photons. All these secondary photons (both products of $\pi^0$ decays and the synchrotron photons) affect the EGRET bound on equal footing with the original photons. Thus, multiple scatterings are required in order to further suppress the photon flux. The number $N$ of these scatterings, by which the right hand sides of Eqs. (2), (3) should be multiplied, can be estimated as follows.

Numerical analysis of the $Z$ burst scenario demonstrates [19, 15, 16] that the required energy flux $\mathcal{E} \equiv E^2 j(E)$ in neutrinos at energy $E \approx E_{\text{res}}$ is certainly not less than

$$\mathcal{E}_\nu(E_{\text{res}}) \simeq 5 \cdot 10^4 \text{ eV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}.$$  

(4)

If all these neutrinos are produced in $\gamma p$ or $pp$ collisions, then they are accompanied by the photon flux $\mathcal{E}_\gamma(E_{\text{res}}) \sim \mathcal{E}_\nu(E_{\text{res}})$ (the exact ratio of photon and neutrino fluxes depends on the process which dominates). This flux has to be reduced by a factor of $\sim 50$ in order not to overshoot the EGRET bound [12] of $\sim 10^3$ eV cm$^{-2}$ s$^{-1}$ sr$^{-1}$. As at each $\gamma p$ collision the photon energy flux, $\mathcal{E}_\gamma$, becomes roughly two times smaller, the required number of collisions is $N \gtrsim 6$.

Let us turn now to possible sources of UHE particles. The active galaxies, and BL Lac type objects in particular, provide exceptional conditions for proton acceleration. The BL Lacs are a subclass of blazars without emission lines in spectra. The blazars are active galaxies whose jets are pointing towards us. It is believed that they differ from other active galaxies only by viewing angle (see Ref. [20] for a review). So, some information about structure and physics of these objects can be gained from observation of usual active galaxies.

A typical active galaxy consists of three parts: the core, or active galactic nucleus (AGN); the jets; and the lobes. It is believed that the core is fuelled by a central black hole, which produces two relativistic jets in opposite directions. The matter content of the jets is not very well known, but it is often supposed that a significant part of the jet energy is

\[\text{In our estimate, we took into account that UHE electrons and positrons lose their energy mostly into synchrotron photons of high energy and neglected the fact that } \sigma_{\gamma p} \text{ is smaller for these photons in comparison with primary UHE photons. As a result, we obtained a conservative estimate for } N.\]
carried by protons. The jets are highly collimated, with beaming angle of a few degrees.\textsuperscript{3} The jets end in the lobes, clouds of non-relativistic matter which are fuelled by the particle fluxes of the jets. At the end of the jet the so-called “hot spot” is formed. The typical size of a hot spot in the transverse direction (and the typical width of a jet) is \cite{21} of order $1 \div 10$ kpc. Among the active galaxies studied in Ref. \cite{21} only few hot spots exhibit $l_{\perp} \sim l_{\parallel}$, while the most have $l_{\parallel}$ about 0.3 kpc.

We can now use the density and mass limits obtained above to rule out blazar jets and hot spots as photon absorption sites. First, for $l_{\parallel} \sim 0.3 \div 3$ kpc, the required proton density (2) is at least a few orders of magnitude higher than observed.\textsuperscript{4} Second, for a typical size $l_{\perp}$ of a hot spot (and jet) of order a few kiloparsecs, the total mass of the \textit{baryonic} part of the absorption site should be of order $10^{14} M_\odot$ (see Eq. (3)). This exceeds by an order of magnitude the mass of the heaviest known galaxies (extremely rare giant galaxies) \cite{23} and by two orders of magnitude the mass of a typical active galaxy \cite{24}.

A protonic cloud is the most economic way to suppress the photon flux because of large $\gamma p$ cross section and the fact that energy transfers from electromagnetic channel into neutrinos. Alternatives to the protonic absorption region are \textit{i}) a cloud filled with a large number of soft photons and \textit{ii}) a region with very strong magnetic field. The latter possibility is less attractive because the energy remains in the electromagnetic channel, and for less energetic secondary photons the interaction with the magnetic field is strongly suppressed.

So, let us consider an absorption site filled by photons. In a way similar to Eqs. (2), (3), we estimate the required photon density,

$$n_{\gamma} > \frac{1}{\sigma_{\gamma\gamma} l_{\parallel}} \approx 5 \cdot 10^7 \left( \frac{6 \mu b}{\sigma_{\gamma\gamma}} \right) \left( \frac{1 \text{ kpc}}{l_{\parallel}} \right) \text{ cm}^{-3},$$

and the total energy of the photons which fill the absorbing cloud:

$$E_{d}^{\gamma} \sim \omega_{\gamma} n_{\gamma} l_{\perp}^2 l_{\parallel} > \omega_{\gamma} l_{\parallel}^2 n_{\gamma} \approx 2 \cdot 10^{13} M_\odot \left( \frac{\omega_{\gamma}}{10 \text{ MeV}} \right) \left( \frac{l_{\perp}}{1 \text{ kpc}} \right)^2 \left( \frac{6 \mu b}{\sigma_{\gamma\gamma}} \right).$$

Here, $\omega_{\gamma}$ is the average energy of soft photons. For not very energetic photons, such that the center-of-mass energy $E_{cm} \lesssim 10^{17}$ eV in photon-photon collisions, the dominant process is double pair production with cross section of about $6 \mu b$. For higher $E_{cm}$ multipion production is important, but the corresponding cross section depends logarithmically on the energy $\omega_{\gamma}$ and even at low energy, $E_{cm} \sim 1$ TeV, the partial cross section for this channel is about ten percent. Thus most part of the energy remains in the electromagnetic channel: energy transfer into neutrinos in soft photonic cloud is suppressed by multipion branching ratio, so the required number of collisions $N$ is larger than in the case of protonic cloud. Also, $\sigma_{\gamma\gamma} \gtrsim 6 \mu b$ and this cross section grows with energy (at high $\omega_{\gamma}$) logarithmically, which means that the total energy in photons, Eq. (6), grows with $\omega_{\gamma}$. The corresponding value of $E_{d}^{\gamma}$ exceeds the mass of a galaxy, contrary to the astrophysical estimates \cite{23}. This

\textsuperscript{3}Since no correlation was found between the arrival directions of UHECRs and positions of active galaxies seen by large angles, we suppose that the neutrino flux is also highly collimated, in the same direction as a jet.

\textsuperscript{4}The density of electrons in a hot spot of a particular active galaxy was estimated \cite{22} as $n_e \sim 500 \text{ cm}^{-3}$. We assume that the proton density is of the same order.
means that the blazar jets and hot spots cannot be optically thick due to photons with $\omega_\gamma \gtrsim 1$ MeV.

In order to rule out the possibility to suppress UHE photon energy flux by scattering off photons with energies $\omega_\gamma < 1$ MeV we estimate the soft photon density in the blazars. To this end, we consider the most extensively studied blazar, Mrk 421. The observational data [25] concern photons with frequencies $\nu > 10^8$ Hz ($\omega_\gamma > 4 \times 10^{-7}$ eV). The flux of Mrk 421 as a function of $\nu$ exhibits a plateau of $\sim 1$ Jy at $\nu = 10^8 \div 10^{10}$ Hz, and decreases monotonically at higher frequencies. Assuming that all photons produced in the source escape without significant energy loss, and that the total luminosity of a blazar is produced in an absorption site of the size $\sim 1$ kpc, we may estimate the photon number density at $\nu = 10^8 \div 10^{10}$ Hz,

$$n_\gamma \lesssim 3 \cdot 10^3 \text{ cm}^{-3}; \quad (7)$$

at higher $\nu$ the number density is smaller. Eq. (7) is consistent with the observational evidence for $n_\gamma \simeq 10^3 \text{ cm}^{-3}$ in a lobe of a particular active galaxy [26]. This density is much less than the one required for optical thickness, Eq. (5), which means that the photons with energies $\omega_\gamma < 1$ MeV cannot help to make AGN jets/hot spots optically thick with respect to $\gamma\gamma$ interactions.

The only way to weaken the requirement (5) is to fine-tune the energy of the soft photons in order to get the maximal cross section $\sigma \sim 0.2 \text{ b (e}^+\text{e}^- \text{ pair production at energy close to threshold)}$. In particular, UHE photons with energy of $E_\gamma \sim 10^{19} \div 10^{23}$ eV scatter with such a large cross section off soft photons with frequencies $\nu \sim 10^3 \div 10^7$ Hz. There are no experimental data on the number density of photons of such low frequencies in blazars. If at lower frequencies the number density is the same as at $\nu \sim 10^8 \div 10^{10}$ Hz, Eq. (7), photons with energies $E_\gamma \sim 10^{16} \div 10^{23}$ eV can scatter off soft photons once at most. However, this cannot help to avoid EGRET bound because for $e^+e^-$ production near threshold the energy remains in the electromagnetic channel.

To summarize, the ultra-high energy neutrino flux required in the Z-burst mechanism cannot be produced in blazar jets and hot spots, since the latter do not have enough mass and density to suppress the accompanying ultra-high energy photon flux. If not suppressed by about two orders of magnitude, these photons would cascade towards lower energies and overshoot the EGRET limit.

One can estimate parameters of a neutrino source required to suppress the photon flux in the Z-burst scenario. As follows from Eqs. (2), (3), (5), (6), the linear size of the dense part of such a source should not exceed 300 pc, and proton density $n_p$ has to be larger than $10^6 \text{ cm}^{-3}$, or photon density $n_\gamma$ significantly larger than $10^9 \text{ cm}^{-3}$ (we take into account the large number of collisions $N$). Among the known astrophysical objects capable to accelerate particles up to ultra-high energies, only AGN cores, neutron stars and gamma ray bursts could satisfy these criteria.

### 3 Secondary neutrino flux

Let us study now the features of the neutrino spectrum of a hypothetical optically thick source of UHE neutrinos required for the Z-burst mechanism. Scatterings in a dense protonic cloud (or in a cloud of very high energy photons) result in a significant flux of lower-
energy neutrinos which escape from the source. We estimate the flux of these secondary neutrinos and confront the “Z-burst plus optically thick sources” scenario with measured fluxes of high-energy neutrinos.

The required neutrino energy flux $E_\nu(E_{\text{res}})$ corresponds to a narrow bin, $E_{\text{res}} - \Delta E \lesssim E \lesssim E_{\text{res}} + \Delta E$, where $\Delta E \approx 0.03 E_{\text{res}}$ is the width of the $Z$ resonance. To get a lower bound on the flux of the secondary neutrinos we suppose that the original flux is zero at other energies (which, of course, is not the case in a realistic source). We assume that the relevant total $\gamma p$ and $\gamma \gamma$ cross sections are saturated by multi-pion production. The average multiplicity in high-energy collisions is a mild monotonically growing function of the energy (see, e.g., Refs. [27]), and for the energy scale of interest it can be approximated by a constant, $\langle n \rangle \sim 500$. The average energy of each of the pions after the first collision is $E_{\text{res}}/\langle n \rangle$, and approximately one third of the total energy is carried by neutral pions and the rest — by charged pions. Neutral pions decay to photons of lower energy which, in turn, initiate new $p\gamma$ and/or $\gamma \gamma$ collisions (remember that $N \gtrsim 6$ collisions are required to suppress the gamma ray flux below EGRET values). Charged pions from each collision decay to leptons, and the resulting neutrino flux is easily estimated. We present the estimates of the high-energy secondary neutrino flux in Fig. 1, where the experimental bounds are also shown. Note that UHE nucleons which scatter off non-relativistic protons also produce secondary UHE neutrinos. This results in additional contributions to the neutrino flux which can be considered on equal footing with those from $\gamma p$ and $\gamma \gamma$ collisions. At very high energies, these processes again are dominated by multipion production, and their analysis is very similar to that of the $\gamma p$ case.

Though our estimates are fairly rough because exact details of ultra-high energy and high-multiplicity processes are complicated and sometimes unknown, our approach allows to check the viability of various astrophysical sources to produce UHE neutrino flux required by the “Z-burst plus optically thick sources” mechanism. As is seen from Fig. 1, the projected sensitivities of future experiments to neutrino flux at high energies are sufficient to check the possibility that the enormous flux of photons required by the $Z$-burst mechanism is suppressed in a protonic cloud, or in a cloud of very high energy photons, no matter what are the parameters of the source.

If the photonic cloud consists of less energetic photons, then double pair production dominates, and details of the neutrino spectrum depend on the magnetic field in the cloud. The energy flux of neutrinos is suppressed then by multipion branching ratio with respect to values shown in Fig. 1. However, the remaining secondary neutrino flux is still within the projected sensitivity of high-energy neutrino experiments.

On the other hand, if the absorption site is full of very soft photons with $\nu \lesssim 10^7$ Hz, the only contribution to the neutrino flux would come from the first $\gamma p$ collision and only neutrinos at energy $E_{\text{res}}$ would be produced. Perspectives for detection of these neutrinos were discussed in a number of papers on the $Z$-burst mechanism (see, e.g., Refs. [19, 17, 16]).

4 Conclusions

Together with neutrinos required for the $Z$-burst explanation of UHE cosmic rays, a certain number of energetic photons are produced in astrophysical accelerators. Propagation of these photons in the intergalactic space results in their reprocessing into softer gamma
Figure 1: Bold arrows represent the estimates of the total ($\nu_e + \bar{\nu}_e + \nu_\mu + \bar{\nu}_\mu + \nu_\tau + \bar{\nu}_\tau$) neutrino flux from optically thick sources for $E_{\text{res}} = 1.5 \cdot 10^{22}$ eV (favoured by Ref.[17]). Solid lines represent current bounds from MACRO [28], Baikal [29], AMANDA [30], RICE [31], GLUE [32], AGASA [33], and Fly’s Eye [4]. Projected sensitivities (dashed lines) of NT-200+ [29], AMANDA-2 [34], ANTARES [35], IceCube [36], Gigaton [29], Mount [37], Pierre Auger [38], Telescope Array (TA) [39], OWL [40], and EUSO [41] are also shown. For TA (10 stations), OWL, and EUSO we assumed 10% duty factor, one event per year detection threshold, and neutrino-nucleon cross sections from Ref.[42]. Thick lines (and a point) correspond to “model-independent” limits which assume monochromatic neutrino fluxes, thin lines correspond to $E^{-2}$ assumed neutrino spectrum. All limits were recalculated with 1:1:1 flavour ratio suggested by results on neutrino oscillations [43].
rays with energies detectable by EGRET. If high-energy photons escape from the sources, the resulting gamma-ray background is inconsistent with EGRET observations for uniform source distribution. The sources, therefore, have to be opaque to ultra-high energy photons. We estimated the required mass and the size of the absorption region and found that jets and hot spots of active galaxies (blazars, radio galaxies, etc.) cannot be optically thick to UHE photons. They are, therefore, excluded as “engines” of the Z-burst scenario. We then analyzed the flux of the secondary neutrinos which are produced in the process of photon absorption in a hypothetical optically thick source and obtained further constraints. We argued that future measurements of neutrino flux at high energies will test the “Z-burst plus optically thick protonic sources” scenario. Our results are relevant not only for the Z-burst mechanism but for any other mechanism which requires high flux of photons in the source of cosmic rays.

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