The theoretical predictions of Ultra-High Energy Neutrino Fluxes *

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Abstract

The review of extragalactic neutrino fluxes above 10^{14} eV was made in various scenarios and how they are constrained by current data. The analysis is based on recently developed propagation code. The detailed calculations showed that maximal cosmogenic neutrino flux, produced by pion production of ultra high energy cosmic rays outside their sources, is considerably higher than the "Waxman-Bahcall bound". Such fluxes would significantly increase the chances to detect ultra-high energy neutrinos with experiments currently under construction or in the proposal stage.

1 Introduction

Motivated by the increased experimental prospects for ultra-high energy neutrino detection, in the present work we reconsider flux predictions in several modern scenarios. Our main emphasize is thereby on model independent flux ranges consistent with all present data on cosmic and $\gamma-$rays. For any scenario involving pion production the fluxes of the latter are comparable to the neutrino fluxes. However, electromagnetic (EM) energy injected above $\sim 10^{15}$ eV cascades down to below the pair production threshold for photons

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[*] Based on results of paper [1]

on the CMB. The cascade thus gives rise to a diffuse photon flux in the GeV range which is constrained by the flux observed by the EGRET instrument on board the Compton $\gamma-$ray observatory [2]. For all neutrino flux scenarios the related $\gamma-$ray and cosmic ray fluxes have to be consistent with the EGRET and cosmic ray data, respectively.

In the present investigation recently combined propagation codes [3, 4] were used. We parameterize power law injection spectra of either protons (for ultra high energy cosmic ray (UHECR) sources) or neutrinos (for Z-burst models) per comoving volume in the following way:

$$\begin{aligned} \phi(E,z) &= f(1+z)^m\, E^{-\alpha}\Theta(E_{\rm max}-E) \\ & \qquad z_{\rm min} \le z \le z_{\rm max}\,, \end{aligned} \tag{1}$$

where f is the normalization that has to be fitted to the data. The free parameters are the spectral index α, the maximal energy $E_{\rm max}$, the minimal and maximal redshifts $z_{\rm min}$, $z_{\rm max}$, and the redshift evolution index m. The resulting neutrino spectra depend insignificantly on $z_{\rm min}$ in the range $0 \le z_{\rm min} \lesssim 0.1$ where local effects could play a role, and thus we will set $z_{\rm min} = 0$ in the following.

To obtain the maximal neutrino fluxes for a given set of values for all these parameters , we determine the maximal normalization f in Eq. (1) by demanding that both the accompanying nucleon and $\gamma-$ray fluxes are below the observed cosmic ray spectrum and the diffuse $\gamma-$ray background observed by EGRET, respectively.

2 The Cosmogenic Neutrino Flux

The flux of ”cosmogenic” neutrinos created by primary protons above the Greisen-Zatsepin-Kuzmin (GZK) cutoff [5] in interactions with CMB photons depends both on primary proton spectrum and on the location of the sources.

If sources are located beyond the GZK distance and the proton flux extends beyond the GZK cutoff, the neutrino fluxes can be significant.

Fig. 1 illustrates dependence of cosmogenic neutrino flux on the injection spectrum power law index α. In our calculations we used $B = 10^{-9}$ G and the intermediate URB strength estimate of Ref. [6]. These parameters only influence the $\gamma-$ray flux at ultra high energies (UHE), but not in the GeV range where the flux only depends on the total injected EM energy. Therefore, in this scenario the resulting neutrino fluxes are insensitive to

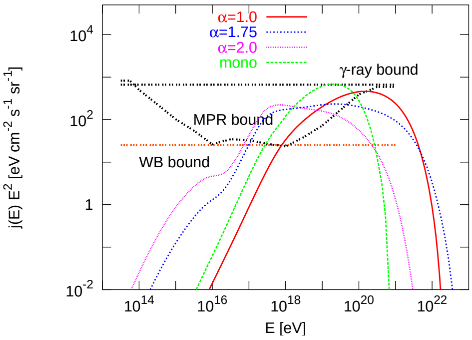


Figure 1: Dependence of the average cosmogenic neutrino flux per flavor maximized over maximal injection energy $E_{\rm max}$, evolution index m, and normalization consistent with all cosmic and $\gamma-$ray data, on the injection spectrum power law index α. "mono" indicates monoenenergetic proton injection at $E = 10^{21}\,$eV.

the poorly known UHE $\gamma-$ray absorption because the "visible" UHE flux is always dominated by the primary cosmic rays and not by the secondary $\gamma-$ray flux, as can be seen in Figs. 2 and 3 below. For more details about the spectra dependence on the parameters of model (1) see ref. [1]. Fig. 1 shows that cosmogenic neutrino fluxes higher than both the Waxman-Bahcall (WB) and Mannheim, Protheroe, Rachen (MPR) limits [7, 8] are possible even for relatively soft E^{-2} proton injection spectra, if the redshift evolution is stronger than for AGNs: The curve for E^{-2} in Fig. 1 corresponds to the evolution parameters $m = 5$, $z_{\rm max} = 3$ and $E_{\rm max} = 10^{22}\,$eV, the curve for $E^{-1.75}$ to $m = 4.5$, $z_{\rm max} = 3$ and $E_{\rm max} = 10^{23}\,$eV, and the curve for monoenergetic injection to $m = 4$, $z_{\rm max} = 3$, and $E_{\rm max} = 10^{21}\,$eV.

Between $\sim 10^{18}\,$eV and $\sim 10^{20}\,$eV the energy loss rate of protons on the CMB is dominated by pair production instead of pion production. The former does not contribute to neutrino production but the EM cascades initiated by the pairs lead to contributions to the diffuse $\gamma-$ray background in the GeV range. Thus, the cosmogenic neutrino flux is the more severely constrained the bigger the fraction of cosmic ray power is in the range $10^{18}\,{\rm eV} \lesssim E \lesssim 10^{20}\,$eV. This is mostly important for soft injection spectra and explains why the total neutrino energy fluence decreases with increasing α in Fig. 1.

In any scenario involving pion production for the creation of $\gamma-$rays and neutrinos, the fluxes are approximately related by $F_\nu(E) \approx F_\gamma(E)/3$. Assuming smooth spectra and comparing with the EGRET $\gamma-$ray fluence, energy conservation implies

$$E^2 F_\nu(E) \lesssim 6 \times 10^2 \, \mathrm{eV cm^{-2} s^{-1} sr^{-1}} \,. \tag{2}$$

This ultimate bound is also shown in Fig. 1. MPR limit for optically thick sources coincide with this limit, because it is based on the same EGRET bound. The maximal $E^2 j(E)$ of the fluxes in Fig. 1 indeed reach this $\gamma-$ray bound Eq. (2). However, physics of both cases is different.

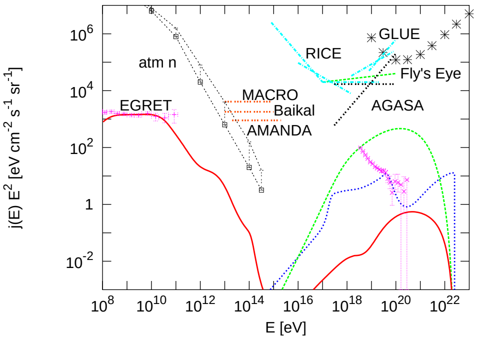


Figure 2: A scenario with maximal cosmogenic neutrino fluxes as obtained by tuning the parameters to $z_{\max} = 2$, $E_{\max} = 10^{23}\,\mathrm{eV}$, $m = 3$, $\alpha = 1$. Also shown are predicted and observed cosmic ray and $\gamma-$ray fluxes, the atmospheric neutrino flux, as well as existing upper limits on the diffuse neutrino fluxes.

Figs. 2 and 3 shows a scenario maximized over all 4 parameters in comparison to existing neutrino flux upper limits and expected sensitivities of future projects, respectively. The maximized fluxes should be easily detectable by at least some of these future instruments, as is obvious from Fig. 3

3 Active galactic nuclei as UHECR sources

Active galactic nuclei (AGN) can be sources of neutrinos if protons are accelerated in them. In the present paper we consider only the two representative limits of low and high optical depth for pion (and neutrino) production in the source. In the first case the protons accelerated in the AGN freely escape and

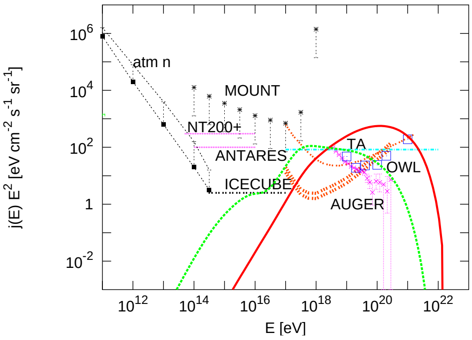


Figure 3: The cosmogenic neutrino flux shown in Fig. 2 in comparison with expected sensitivities of the currently being constructed Auger project to electron/muon and tau-neutrinos, and the planned projects telescope array, the fluorescence Cherenkov detector MOUNT, and the space based OWL (we take the latter as representative also for EUSO), the water-based NT200+, ANTARES, and the ice-based ICECUBE, as indicated. Also shown is an extreme scenario with $z_{\rm max} = 3$, $E_{\rm max} = 10^{22}\,$eV, $m = 5$, and $\alpha = 2$, leading to a cosmogenic neutrino flux extending to relatively low energies where ANTARES and ICECUBE will be sensitive, and the atmospheric neutrino flux for comparison.

neutrinos are produced only in interactions with the CMB (cosmogenic neutrinos). Let us assume typical evolution parameters $m = 3.4$ for $z < 1.9$ and $m = 0$ for $1.9 < z < 2.9$ [9]. The remaining free parameters are the power law index α, the maximum energy $E_{\rm max}$ for the proton injection spectrum, and the flux normalization f in Eq. (1).

Fig. 1 demonstrate in a general way that it is easy to exceed the WB bound for injection spectra harder than about E^{-2}. This is because Waxman-Bahcall restricted themselves to nucleon injection spectra softer than E^{-2} and sources smaller than nucleon interaction lengths [7]. Curves for monochromatic flux and 1/E on fig. 1 were calculated assuming AGN evolution of sources. 1/E is in agreement with MPR-bound as it should be (note that they draw their curve through maximums of neutrino fluxes), while monochromatic exceeds even MPR.

For the case of high optical depth for pion production let us discuss an example of possible high neutrino fluxes from a non-shock acceleration AGN model [10], in which primary protons lose all their energy and produce neutrinos directly in the AGN core.

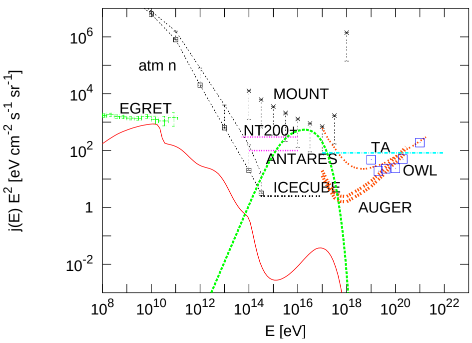


Figure 4: Neutrino flux predictions for the AGN model [10] for a uniform distribution of blazars (no redshift evolution). Photon flux is below measured EGRET value. The typical neutrino flux in this model contains the same energy as the photons. The position of the peak is governed by the initial proton distribution. The line key is as in Fig. 3.

In this model the VHE γ-rays are produced by accelerated protons interacting with the ambient photon fields (supplied, for example by the accretion disk around the massive black hole) through photo-meson processes. At the same time those protons produce neutrinos which are emitted in the direction of the jet. Therefore, this model predicts a high neutrino flux comparable in power with the γ-ray flux. The detailed numerical simulations of proton acceleration in the central engine of the AGN show that the collimated jet of almost monoenergetic VHE protons (linear accelerator) can be created in the electro-magnetic field around the black hole and the energy of those protons can be converted into photons and neutrinos, while protons can be captured inside of the source. The nucleon flux leaving the AGN is well below observed cosmic ray flux in this scenario. Furthermore, since all nucleons leaving the source are well below the GZK cutoff, there is no cosmogenic contribution to the neutrino flux from these sources.

Fig. 4 shows a typical prediction of the diffuse neutrino flux in this scenario. This flux is beyond the WB limit which is not applicable in this case because the sources are optically thick for nucleons with respect to pion photoproduction. The flux is consistent with MPR bound for optically thick sources.

In the AGN model discussed above, blazars would be seen by neutrino telescopes as point-like sources with neutrino fluxes which are smaller or of the same order as the photon flux emitted by these same sources and which are detectable by γ-ray telescopes.

In the AGN model discussed above, the neutrino flux from point-like sources like blazars can be much larger then photon flux from same objects due to stronger collimation of neutrino flux (this is not true for diffuse flux, because collimation reduces total number of sources) [11].

4 Neutrino Fluxes in Top-Down Scenarios

In top-down scenarios UHECRs are the decay products of some supermassive “X” particles of mass $m_X \gg 10^{20}\,\mathrm{eV}$ close to the grand unified scale, and have energies all the way up to $\sim m_X$. The X particles typically decay into leptons and quarks. The quarks hadronize, producing jets of hadrons which, together with the decay products of the unstable leptons, result in a large cascade of energetic photons, neutrinos and light leptons with a small fraction of protons and neutrons, some of which contribute to the observed UHECR flux. The resulting injection spectra have been calculated from QCD in various approximations. The spectra used in present work are shown in Fig. 11 of [1] They were obtained from solving the DGLAP equations in modified leading logarithmic approximation (MLLA) without supersymmetry for X particles decaying into two quarks, assuming 10% nucleons in the fragmentation spectrum.

Averaged X particle injection rate is taken in the form

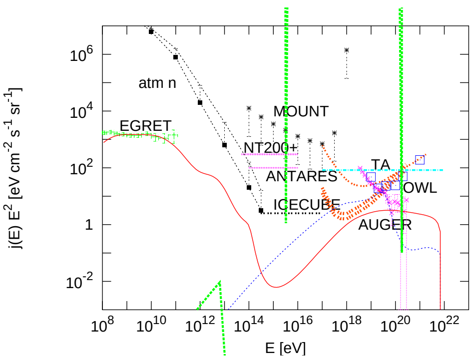
$$\dot{n}_X(t) =\propto m_X \times t^{-3}\,, \tag{3}$$

which corresponds to the model with extragalactic topological defect sources.

Fig. 5 shows the results for $m_X = 2 \times 10^{14}\,\mathrm{GeV}$, with $B = 10^{-12}\,\mathrm{G}$, and again the minimal URB consistent with data [6]. These parameters lead to optimistic neutrino fluxes for the maximal normalization consistent with all data.

5 The Z-Burst Scenario with Acceleration Sources

In the Z-burst scenario UHECRs are produced by Z-bosons decaying within the distance relevant for the GZK effect. These Z-bosons are in turn produced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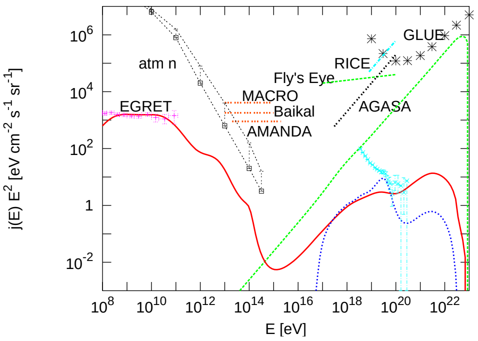

Figure 6: Flux predictions for a Z-burst model averaged over flavors and characterized by the injection parameters $z_{\rm min} = 0$, $z_{\rm max} = 3$, $\alpha = 1$, $m = 0$, in Eq. (1) for neutrino primaries. All neutrino masses were assumed equal with $m_\nu = 0.1$ eV and we again assumed maximal mixing between all flavors. The line key is as in Fig. 2.

scenarios with cosmic ray injection spectra harder than $E^{-1.5}$, maximal energies $E_{\rm max} \gtrsim 10^{22}\,$eV, and redshift evolution typical for quasars, or stronger. Given our poor knowledge on the origin of UHECRs, in our opinion these are possibilities that should not be discarded at present, especially since they would lead to considerably increased prospects of ultra-high energy neutrino detection in the near future. We also show that for non-shock AGN acceleration models the AGN neutrino fluxes can reach the $\gamma-$ray bound Eq. (2) around $10^{16}\,$eV which represents the ultimate limit for all scenarios of $\gamma-$ray and neutrino production involving pion production.

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