Extraterrestrial diffuse flux of PeV scale neutrinos from accretion disk regions of active galactic nuclei

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Introduction

The 2010–2017 data observed by the Ice-Cube experiment altogether contributed a total of five neutrino events nearly in the 1–10 PeV range [1]. The hadronic interaction processes like pγ and pp are believed to be responsible in astrophysical sites for the production of these ultra-high-energy (UHE) neutrinos. The active galactic nuclei (AGNs) with appropriate bolometric luminosities are considered in the present work as probable sources of extragalactic PeV neutrinos. The accretion disk region is likely to be the production site of these neutrinos.

The UHE protons with median energies of the order of 0.1 EeV, might generate neutrinos through the pion photo-production interactions in the accretion disk zone. UV and soft X-ray radiations are very abundant ($p_{\rm rad} \gg p_{\rm gas}$, the radiation and gas pressures) in the region of the accretion disk around an AGN. The highly energetic protons follow dominant photo-pion production leading to the Δ resonance in the dense radiative zone. The Δ^+ resonance state goes to decay via the following channels [2]:

$$p+\gamma \to \Delta^+ \to \begin{cases} p+\pi^{\rm o} \to p+2\gamma \\ n\pi^+ \to n+e^+ +\nu_{\rm e}+\nu_\mu+\bar{\nu_\mu} \end{cases} \quad (1)$$

If the above processes in eq. (1) contribute the PeV neutrino events, there should be a supply of UHE protons with energies all the way close to the range $\sim 0.01-0.5$ EeV. Such protons/electrons could indeed be driven successfully by the AGN via the Landau damping of centrifugally driven Langmuir waves [1]. The pumping of rotational energy in the magnetosphere of AGNs into the electric field in the vicinity of the light cylinder surface efficiently supplies the energy for growing Langmuir waves in the bulk electron-proton plasma. The excited Langmuir waves then damp on a faster local proton/electron beam, accelerating them to higher energies. The acceleration mechanism is called the Langmuir-Landau-Centrifugal-Drive (LLCD), has been applied to accelerate protons in plasmas surrounding an AGN [2].

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Proton and neutrino energies

As a consequence of the Langmuir collapse, the protons are accelerated to desired energy as follows,

$$\epsilon_p \approx \frac{ne^2}{4\pi^2\lambda_D^3}\Delta r^5 \ (eV). \quad (2)$$

where $\lambda_{\rm D}$ is the Debye length and Δr is a narrow length-scale region in the vicinity of the light cylinder. Taking $\Delta r \approx \frac{\rm R_{lc}}{2\gamma_p}$ and $L_{43} \equiv \frac{L_b}{(10^{43}\ erg\ s^{-1})}$, and also $\rm R_{lc,8} \approx 3\times 10^{14} M_8$ cm, the above equation reduces to

$$\epsilon_p \approx 1.14\times10^{17}\times(\frac{f}{10^{-3}})^3\times(\frac{10^2}{\gamma_p})^5\times(\frac{L_{43}}{M_8})^{5/2}\ (eV), \quad (3)$$

where $\rm f = \frac{\delta n}{n_0}$ is the initial number density perturbation, and we have chosen $\eta_c \approx 0.1$ and $a \approx 0.1$ whenever required.

Here, we assume that each PeV neutrino could receive $\approx 4\%$ on the average of the energy of the proton via the reaction channel in eq. (1).

$$E_\nu \approx 0.04E_p \approx 2(PeV)\ \epsilon_{p,17}[2/(1+z)]. \quad (4)$$

Here, $\epsilon_{\rm p} = \epsilon_{p,17}(10^{17}eV)$, being the proton energy in the cosmic rest frame and z is the gravitational red-shift of the source. This work mainly includes AGNs in the red shift interval, $0.002 < z \leq 6$ with bolometric luminosities in a certain range.

The most abundant synchrotron loss mechanism does not affect the continuous energy acquiring mode of protons. In addition, the cooling time-scale of the ICS process by protons is a continuously increasing (or slow process) function of $\epsilon_{\rm p}$. The next possible energy loss process is the curvature radiation, is also a weak process for losing energy by protons. In the LLCD model, the cooling time-scales of *pp* scattering, and Bethe-Heitler (BH) pair production on disk photons, do not have noticeable effect to prevent protons for exceeding photomeson production energies.

Diffuse neutrino flux

The derived flux of UHE protons after evaluating different integrals with appropriate limits according to the Luminosity-dependent density evolution (LDDE) model for the XLF takes the form [2],

$$\Phi_{p,d} \approx 7.2 \times 10^{86} \times \frac{cA_* \xi_{p\gamma} \eta_k}{4\pi H_0 L_*}. \quad (5)$$

in erg cm^{-2}s^{-1}sr^{-1}.

Hence, the muon neutrino flux contributed by all the AGNs with $z = 0.002$–6 and $L_b = (0.545$–$2.98) \times 10^{43}$ erg s^{-1} is [2]

$$\Phi_{\nu_\mu/\gamma} \approx 4.46 \times 10^{89} \times \frac{cA_* \xi_{p\gamma} \eta_k \chi_r \chi_o}{4\pi H_0 L_*}. \quad (6)$$

in GeV cm^{-2}s^{-1}sr^{-1}.
Using other relevant parameters available in the paper, the PeV muon neutrino flux resulting from the theory with the LDDE model for the XLF, is, $3.98 \times 10^{-8}\eta_k$ in GeV cm^{-2}s^{-1}sr^{-1}.

Using Luminosity-dependent density evolution (LDDE) model with photon index distribution, the derived diffuse PeV muon neutrino flux from AGNs is [1-2]

$$\Phi_{\nu_\mu/\gamma} \approx 5.03 \times 10^{-8}\eta_k. \quad (7)$$

in GeV cm^{-2}s^{-1}sr^{-1}.

The diffuse flux of muon neutrinos observed at Earth in the energy range, $\approx$ 1–10 PeV could be [1-2]

$$\Phi_{\nu_\mu,d} = \int_1^{10} E_\nu{}^{-1} J_\nu(E_\nu) dE_\nu \approx 2.59 \times 10^{-9} \quad (8)$$

in GeV cm^{-2}s^{-1}sr^{-1}.

For the LDDE modeled XLF, it is found that the model predicted flux could give the IceCube measured PeV neutrino flux per flavor if $\eta_{\rm k}$ takes a value $\approx$ 6.5%. Finally, exploiting the Λ CDM cosmology along with the photon index distribution in the LDDE modeled XLF, the factor η_k becomes $\approx$ 5.2%. In case of single-power-law LF (though it is outdated nowadays and hence the calculation is not shown) without the AGN cosmological evolution, the parameter $\eta_{\rm k}$ is found close to $\approx$ 0.005%.

Conclusions

The estimated diffuse muon neutrino flux using the Λ-CDM cosmology for the AGN LF is found consistent with one that has been predicted by erstwhile standard FRW cosmology. In our model calculation, it has been found that a certain fraction of the total bolometric luminosity of AGNs in the universe is just enough to interpret the PeV energy neutrino flux observed by IceCube. The extragalactic diffuse PeV gamma rays produced simultaneously with neutrinos are unlikely to be available at Earth because of their strong absorption en route.

References

[1] R. K. Dey *et al. Braz J Phys* **51**, 1406 (2021);

[2] R. K. Dey *et al.*, Diffuse flux of PeV neutrinos from centrifugally accelerated protons in active galactic nuclei (submitted to *Europhys. Lett.* August 2021).