Testing high energy neutrino emission from the Fermi Gamma-ray Space Telescope Large Area Telescope (4LAC) sources

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The detection of the high-energy neutrino IC-170922A in spatial (within the error region) and temporal flare activity correlation with the blazar TXS 0506+056 allowed these objects to be considered as progenitor sources of neutrinos. Besides this, no more detection of this kind was reported. Some other neutrinos detected by IceCube show a spatial correlation (within the error region) from other Fermi-LAT detected sources. However, these objects did not show a flare activity like TXS 0506+056. Assuming a lepto-hadronic scenario through py interactions, this work describes the SED in some objects from the fourth catalog of active galactic nuclei (AGNs) detected by the Fermi Gamma-ray Space Telescope Large Area Telescope (4LAC) sources, which are in spatial correlation with neutrinos detected by IceCube. Additionally, we estimate the corresponding neutrino flux counterpart from these sources.

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1. Introduction

Cosmic rays (high-energy protons or heavy nuclei) frequently hit the earth with energies greater than $10^{18}$ eV. More than a century since the discovery, places, and processes of acceleration remain in uncertainty. This is due to the electric charge makes that any magnetic field deflects its trajectories to Earth [1]. Fortunately, theoretical models suggest that in their places of acceleration, cosmic rays interact with radiation fields of low energy and with matter to produce high-energy photons and neutrinos [2]. Besides the fact that cosmic rays cannot tell us their production places, gamma rays and neutrinos can. At very high energies (hundred of GeVs), photons are attenuated by the effect of Extragalactic Background Light (EBL) [e.g. 3]. Therefore, a neutrino is an ideal messenger.

2. Observations

We use the muon neutrinos detected by IceCube up to date. For the electromagnetic counterpart, we use the 4LAC-DR2 catalog reported by Fermi-LAT.

2.1 The neutrino sample

The IceCube telescope is located near the Amundsen-Scott South Pole Station. This telescope is buried below the surface, reaching a depth of 2,500 meters. The IceCube Collaboration has made public the information about neutrinos detected principally in two catalogs: The High Energy Starting Event (HESE) [4–6], in which are reported 86 high-energy neutrinos, in addition to 36 neutrino events in the Extremely High Energy (EHE) catalog [7, 8]. Additionally, with the goal of having a rapid response to electromagnetic transients possible associated to neutrinos, a real time alert system was implemented. This system distributes the real time events HESE$^1$ and EHE$^3$ via AMON consortium [9].

2.2 The 4LAC sample

The Fermi satellite was launched in June 2008 and since then scan the sky constantly. The satellite is equipped with two instruments, the Gamma-Ray Burst Monitor (GMB) [10] and the Large Area Telescope (LAT) [11] instruments. Recently, the LAT team released the 4FGL catalog [12, 13], which contains the sources in the sky that emits photons in the energy range from 50 MeV up to 1 TeV covering the first 10 years of operation.

We limit ourselves to test the sub set of Active Galactic Nuclei catalog (4LAC) [14, 15], which contains AGN detected by Fermi-LAT with a galactic latitude ($|b| > 10^\circ$). It compromises 3125 sources: 694 FSRQ, 1125 BL Lacs, 1240 BCU and 66 Non blazar AGN. Formerly, a sub sample that does not belong to 4LAC known as Low Latitude sample ($|b| < 10^\circ$) is considered. This sub sample is constituted by 36 FSRQ, 65 BL Lacs, 260 BCU and 6 non blazar AGNs. In particular, we choose the blazar population of this sample to be associated with high-energy neutrinos.

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$^1$Those alerts are public and can be accessed in [https://gcn.gsfc.nasa.gov/amon_hese_events.html](https://gcn.gsfc.nasa.gov/amon_hese_events.html)

$^2$Those alerts are public and can be accessed in [https://gcn.gsfc.nasa.gov/amon_ehe_events.html](https://gcn.gsfc.nasa.gov/amon_ehe_events.html)
3. Theoretical Model

The Spectral Energy Distribution of the blazar was dominate by non-thermal emission characterized by a double bump. The first one located at low energies (from Radio up to Soft X-rays) is interpreted by synchrotron radiation produced by a population of relativistic electrons ($N_e$) embedded into a magnetic field ($B$) [e.g., 16, 17]. Meanwhile, at higher energies, the mechanism remains in discussion. In a leptonic scenario, the same population of relativistic electrons interacts with the synchrotron photons. Relativistic electrons scatter these photons up to higher energies via the Inverse Compton process (SSC) [e.g., 18, 19]. On the other hand, hadronic processes can take place with the presence of cosmic rays in the plasma that interacts with radiation fields of low energies ($py$) [e.g., 20, 21]. In hadronic processes, neutral pions ($\pi^0$) and charged pions ($\pi^\pm$) are expected [22]. In the case of the $\pi^0$, the channel $\pi^0 \rightarrow \gamma \gamma$ takes place, while for charged pions the channels $\pi^\pm \rightarrow \mu^\pm + \nu_\mu$, and therefore $\mu^\pm \rightarrow e^\pm + \nu_e + \bar{\nu}_e$. From this, it is expected a neutrino rate of $(\nu_e : \nu_\mu : \nu_\tau) = (2:1:0)$ in the source. In average the energy of the $\gamma$-rays is $E_\gamma \sim 1/2E_\pi$ and the neutrinos carry a fraction of energy $E_\nu \sim 1/4E_\pi$ from the parent pions, respectively [23].

3.1 Leptonic Scenario

We adopt the theoretical framework derived by [24]. The synchrotron spectra produced by an electron population with a profile $N'_e(\gamma')$ is described by:

$$ f_{\text{syn}}(\epsilon) = \frac{\sqrt{3} \delta_D^4 \epsilon e^3 B}{4 \pi h d_L^2} \int_1^\infty N'_e(\gamma') R(x) d\gamma', $$

where $\epsilon = h\nu/(m_e c^2)$ is the frequency normalized at the electron mass, $\delta_D$ is the Doppler factor, $e$ the fundamental charge, $h$ the Planck’s constant, $d_L$ the luminosity distance from the source and $R(x)$ is defined in [24]. In the high-energy regime, the SSC spectrum is described by:

$$ f_{\text{ssc}}(\epsilon_s) = \frac{9}{16} \frac{(1+z)^2 \sigma_T \epsilon_s^2}{\pi \delta_D^4 \epsilon_{\text{syn}}^2 \tau_{\text{v,min}}^2} \int_0^\infty \frac{f_{\text{syn}}(\epsilon)}{\epsilon'} d\epsilon' \int_{\gamma_{\text{min}}}^{\gamma_{\text{max}}} \frac{N'_e(\gamma')}{\gamma'^2} F_c(q, \Gamma_e) d\gamma', $$

where $z$ is the redshift, $\sigma_T$ is the Thompson cross section, $t_{\text{var,min}}$ is the variability timescale and $F_c(q, \Gamma_e)$ is the Compton cross section [25].

3.2 Hadronic Scenario

We adopt the hadronic scenario introduced in [26]. A proton population described by their characteristic function $f_p(E_p)$ and the target photon population $f_{ph}(\epsilon)$ is used. We adopt a proton population described by a power law with exponential cut-off and the target photons described by a blackbody profile with energy $kT$. Therefore, the $\gamma$-ray spectra (and secondary leptons $l \in \{e, e^\pm, \nu_\mu \bar{\nu}_\mu, \nu_e \bar{\nu}_e\}$) are described by the equation:

$$ \frac{dN}{dE} = \int_{\eta_0}^{\infty} H(\eta, E) d\eta, $$

where $H(\eta, E)$ is defined as:
\begin{equation}
H(\eta, E) = \frac{m_p^2 c^4}{4} \int_{E}^{\infty} f_p(E_p) \frac{f_{ph}(\eta m_p^2 c^4)}{4E_p} \Phi_{\gamma} \left( \frac{E}{E_p} \right) dE_p .
\end{equation}

The function $\Phi_{\gamma}$ (also $\Phi_I$) is a parametrization of the cross section of the hadronic processes given by [26] over $\eta$. It is defined over the region where this kinematics interactions are allowed.

4. Correlations founded

We apply a spatial correlation based on the angular distance between the high-energy neutrino (track events) detected by IceCube (section 2.1) and the Fermi-LAT blazars reported in 4LAC (section 2.2) considering that a gamma-ray source can be associated with a neutrino spatially if the position of this source relies in the neutrino error region at 90%. The correlations that we found are reported in the Tables 1, 2 and 3. In each table, we report the spatial correlations founded. Table 1 shows the coincidences of the neutrinos reported in the HESE and the EHE catalogs, meanwhile in Table 2 is shown the HESE and EHE alerts reported via AMON. Finally, Table 3 is reported the association founded with the Gold and Bronze alerts.

5. Implementation

We pretend to adjust this model through the $\chi^2$ technique, by adopting the strategy proposed in [24]. In an iterative process on the magnetic field ($B$) and the Doppler factor ($\delta_D$), we find the best values for the Synchrotron and SSC spectra assuming a leptonic scenario, using equations (1) and (2) respectively. Is is worth noting that if an extra component at gamma-rays regime is needed, a hadronic component will be considered through equation (3).

6. Conclusion

We found spatial correlations between high-energy neutrinos (track events) reported by IceCube and blazars that emit gamma-ray photons at high energies. Quasi simultaneous SEDs are being derived around the neutrino arrival times in order to describe them with a same radiative model. Now, we are working in Bayesian blocks [27], which are being applied to the GeV-TeV light curves in order to find flare episodes around the neutrino arrival times.

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Table 1: Correlations found between high-energy neutrinos reported in HESE and EHE catalogs and gamma-rays sources. Using the coordinates (RA and Dec) with the respective uncertainties, we report blazars of the 4LAC associated to each neutrino. The sources marked with a * means that this source belongs to the Low Latitude sample.
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| ID          | GCN NAME          | Energy (TeV) | MJD   | RA (deg) | Dec (deg) | Ang Err (deg) |
|-------------|-------------------|--------------|-------|----------|-----------|---------------|
| 766165_132518 | IceCube-190904A  | -            | 58607.77 | 65.78    | -37.44    | 1.23          |
| ID           | GCN NAME          | Energy (TeV) | MJD   | RA (deg) | Dec (deg) | Ang Err (deg) |
| 4FLG ASSOC   | ASSOC             | RA (deg)     |       | Dec (deg) | Ang Sep (deg) | Type |
| 4FLG J0420.3-3745 | NVSS J042025-374443 | 65.1     | -37.74 | 0.63     | bca       |
| 4FLG J0428.6-3756 | PKS 0426-380      | 67.17      | -37.94 | 1.2    | bll       |
| ID           | GCN NAME          | Energy (TeV) | MJD   | RA (deg) | Dec (deg) | Ang Err (deg) |
| 66688905_132229 | IceCube-190221A  | -            | 58535.35 | 267.36   | -16.93    | 1.23          |
| ID           | GCN NAME          | Energy (TeV) | MJD   | RA (deg) | Dec (deg) | Ang Err (deg) |
| 4FLG ASSOC   | ASSOC             | RA (deg)     |       | Dec (deg) | Ang Sep (deg) | Type |
| *4FLG J1744.9-1727 | 1RXS J174459.5-172640 | 266.23    | -17.45 | 1.2    | bca       |
| *4FLG J1751.6-1750 | NVSS J175120-175112 | 267.9     | -17.83 | 1.04   | bca       |
| ID           | GCN NAME          | Energy (TeV) | MJD   | RA (deg) | Dec (deg) | Ang Err (deg) |
| 12296708_131624 | IceCube-181044A  | -            | 58405.49 | 225.18   | -34.79    | 1.23          |
| ID           | GCN NAME          | Energy (TeV) | MJD   | RA (deg) | Dec (deg) | Ang Err (deg) |
| 4FLG ASSOC   | ASSOC             | RA (deg)     |       | Dec (deg) | Ang Sep (deg) | Type |
| 4FLG J1505.0-3433 | PMN J1505-3432    | 226.25      | -34.55 | 0.91    | bll       |
| ID           | GCN NAME          | Energy (TeV) | MJD   | RA (deg) | Dec (deg) | Ang Err (deg) |
| 38561328_129072 | IceCube-161103   | -            | 57695.38 | 40.82    | 12.55     | 1.1           |
| ID           | GCN NAME          | Energy (TeV) | MJD   | RA (deg) | Dec (deg) | Ang Err (deg) |
| 4FLG ASSOC   | ASSOC             | RA (deg)     |       | Dec (deg) | Ang Sep (deg) | Type |
| 4FLG J0244.7+1316 | GB6 J0244+1320   | 41.19      | 13.27  | 0.8    | bca       |

Table 2: Same as table 1, but with those neutrinos reported via AMON consortium.

| ID          | GCN NAME          | Energy (TeV) | MJD   | RA (deg) | Dec (deg) | Ang Err (deg) |
|-------------|-------------------|--------------|-------|----------|-----------|---------------|
| 50579430_130033 | IceCube-170922A  | 119.98       | 58018.87 | 77.28    | 5.75      | 0.25          |
| ID           | GCN NAME          | Energy (TeV) | MJD   | RA (deg) | Dec (deg) | Ang Err (deg) |
| 4FLG ASSOC   | ASSOC             | RA (deg)     |       | Dec (deg) | Ang Sep (deg) | Type |
| 4FLG J0509.4+0542 | TXS 0506+056     | 77.35        | 5.7    | 0.09    | bll       |

Table 3: Same as table 1, but with golden and bronze alerts.
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