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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 $p\gamma$ 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[2] 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 ($|b| > 10°$). 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 ($|b| < 10°$) 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.

[1]Those alerts are public and can be accessed in `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`

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 (pγ) [e.g. 20, 21]. In hadronic processes, neutral pions (π^0) and charged pions ($\pi^{\pm}$) are expected [22]. In the case of the π^0, the channel $\pi^0 \longrightarrow \gamma\gamma$ takes place, while for charged pions the channels $\pi^+ \longrightarrow \mu^+ + \nu_\mu$, and therefore $\mu^+ \longrightarrow e^+ + \nu_e + \bar{\nu}_\mu$. From this, it is expected a neutrino rate of ($\nu_\mu : \nu_e : \nu_\tau$) = (2:1:0) in the source. In average the energy of the γ-rays is $E_\gamma \sim 1/2 E_{\pi^0}$ and the neutrinos carry a fraction of energy $E_\nu \sim 1/4 E_\pi$ 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:

$$f_{syn}(\epsilon) = \frac{\sqrt{3}\delta_D^4 \epsilon' e^3 B}{4\pi h d_L^2} \int_1^\infty N'_e(\gamma') R(x) d\gamma', \tag{1}$$

where $\epsilon = h\nu/(m_e c^2)$ is the frequency normalized at the electron mass, δ_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:

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

where z is the redshift, σ_T is the Thompson cross section, $t_{var,min}$ 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 and the target photons described by a blackbody profile with energy kT. Therefore, the γ-ray spectra (and secondary leptons $l \in \{e, e^+, \nu_\mu \bar{\nu}_\mu, \nu_e \bar{\nu}_e\}$) are described by the equation:

$$\frac{dN}{dE} = \int_{\eta_0}^\infty H(\eta, E) d\eta\,, \tag{3}$$

where $H(\eta, E)$ is defined as:

$$H(\eta, E) = \frac{m_p^2 c^4}{4} \int_E^\infty \frac{f_p(E_p)}{E_p^2} f_{ph}\left(\frac{\eta m_p^2 c^4}{4E_p}\right) \Phi_\gamma\left(\eta, \frac{E}{E_p}\right) dE_p \,, \tag{4}$$

the function Φ_γ (also Φ_l) is a parametrization of the cross section of the hadronic processes given by [26] over η. 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 χ^2 technique, by adopting the strategy proposed in [24]. In an iterative process on the magnetic field (B) and the Doppler factor (δ_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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						HESE
ID	Energy (TeV)	MJD	RA (deg)	Dec (deg)	Ang Err (deg)	
5	71.4	55512.55	110.6	-0.4	1.2	
4FLG ASSOC		ASSOC	RA (deg)	Dec (deg)	Ang Sep (deg)	Type
*4FGL J0725.8-0054		PKS 0723-008	111.46	-0.91	1.01	bcu
ID	Energy (TeV)	MJD	RA (deg)	Dec (deg)	Ang Err (deg)	
23	82.2	55949.56	208.7	-13.2	1.9	
4FLG ASSOC		ASSOC	RA (deg)	Dec (deg)	Ang Sep (deg)	Type
4FGL J1359.1-1152		2MASS J13592131-1150440	209.83	-11.84	1.7	bcu
ID	Energy (TeV)	MJD	RA (deg)	Dec (deg)	Ang Err (deg)	
38	200.5	56470.11	93.3	14	1.2	
4FLG ASSOC		ASSOC	RA (deg)	Dec (deg)	Ang Sep (deg)	Type
*4FGL J0609.5+1402		NVSS J060922+140744	92.34	14.12	0.87	bcu
ID	Energy (TeV)	MJD	RA (deg)	Dec (deg)	Ang Err (deg)	
44	84.6	56671.87	336.7	0	1.2	
4FLG ASSOC		ASSOC	RA (deg)	Dec (deg)	Ang Sep (deg)	Type
4FGL J2227.9+0036		PMN J2227+0037	336.99	0.61	0.68	bll
ID	Energy (TeV)	MJD	RA (deg)	Dec (deg)	Ang Err (deg)	
58	52.6	56859.75	102.1	-32.4	1.3	
4FLG ASSOC		ASSOC	RA (deg)	Dec (deg)	Ang Sep (deg)	Type
4FGL J0649.5-3139		NVSS J064933-313917	102.39	-31.65	0.78	bll
ID	Energy (TeV)	MJD	RA (deg)	Dec (deg)	Ang Err (deg)	
62	75.8	56987.77	187.9	13.3	1.3	
4FLG ASSOC		ASSOC	RA (deg)	Dec (deg)	Ang Sep (deg)	Type
4FGL J1231.5+1421		GB6 J1231+1421	187.84	14.35	1.05	bll
ID	Energy (TeV)	MJD	RA (deg)	Dec (deg)	Ang Err (deg)	
63	97.4	57000.14	160	6.5	1.2	
4FLG ASSOC		ASSOC	RA (deg)	Dec (deg)	Ang Sep (deg)	Type
4FGL J1039.6+0535		NVSS J103940+053608	159.91	5.6	0.91	bcu
4FGL J1040.5+0617		GB6 J1040+0617	160.13	6.28	0.26	bll
4FGL J1043.6+0654		NVSS J104323+065307	160.84	6.88	0.98	bll
ID	Energy (TeV)	MJD	RA (deg)	Dec (deg)	Ang Err (deg)	
71	73.5	57140.47	80.7	-20.8	1.2	
4FLG ASSOC		ASSOC	RA (deg)	Dec (deg)	Ang Sep (deg)	Type
4FGL J0525.6-2008		PMN J0525-2010	81.36	-20.18	0.94	bcu
						EHE
ID	Energy (TeV)	MJD	RA (deg)	Dec (deg)	Ang Err (deg)	
13	300	55722.43	272.22	35.55	-	
4FLG ASSOC		ASSOC	RA (deg)	Dec (deg)	Ang Sep (deg)	Type
4FGL J1808.8+3522		2MASX J18084968+3520426	272.2	35.34	0.17	bcu

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 a each neutrino. The sources marked with a * means that this source belongs to the Low Latitude sample.

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Amon-HESE

ID	GCN NAME	Energy (TeV)	MJD	RA (deg)	Dec (deg)	Ang Err (deg)	
766165_132518	IceCube-190504A	-	58607.77	65.78	-37.44	1.23	
4FLG ASSOC			ASSOC	RA (deg)	Dec (deg)	Ang Sep (deg)	Type
4FGL J0420.3-3745			NVSS J042025-374443	65.1	-37.74	0.63	bcu
4FGL 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)	
66688965_132229	IceCube-190221A	-	58535.35	267.36	-16.93	1.23	
4FLG ASSOC			ASSOC	RA (deg)	Dec (deg)	Ang Sep (deg)	Type
*4FGL J1744.9-1727			1RXS J174459.5-172640	266.23	-17.45	1.2	bcu
*4FGL J1751.6-1750			NVSS J175120-175112	267.9	-17.83	1.04	bcu
ID	GCN NAME	Energy (TeV)	MJD	RA (deg)	Dec (deg)	Ang Err (deg)	
12296708_131624	IceCube-181014A	-	58405.49	225.18	-34.79	1.23	
4FLG ASSOC			ASSOC	RA (deg)	Dec (deg)	Ang Sep (deg)	Type
4FGL 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)	
38561326_128672	IceCube-161103	-	57695.38	40.82	12.55	1.1	
4FLG ASSOC			ASSOC	RA (deg)	Dec (deg)	Ang Sep (deg)	Type
4FGL J0244.7+1316			GB6 J0244+1320	41.19	13.27	0.8	bcu

Amon-EHE

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	
4FLG ASSOC			ASSOC	RA (deg)	Dec (deg)	Ang Sep (deg)	Type
4FGL J0509.4+0542			TXS 0506+056	77.35	5.7	0.09	bll

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

Golden - Alerts

ID	GCN NAME	Energy (TeV)	MJD	RA (deg)	Dec (deg)	Ang Err (deg)	
134698_40735501	IceCube-201114A	214.29	59167.63	105.25	6.04	1.08	
4FLG ASSOC			ASSOC	RA (deg)	Dec (deg)	Ang Sep (deg)	Type
*4FGL J0658.6+0636			NVSS J065844+063711	104.64	6.6	0.81	bcu

Bronze - Alerts

ID	GCN NAME	Energy (TeV)	MJD	RA (deg)	Dec (deg)	Ang Err (deg)	
134535_41069485	IceCube-200926B	121.42	59118.94	184.75	32.929	1.81	
4FLG ASSOC			ASSOC	RA (deg)	Dec (deg)	Ang Sep (deg)	Type
4FGL J1220.1+3432			GB2 1217+348	185.04	34.53	1.63	bll
ID	GCN NAME	Energy (TeV)	MJD	RA (deg)	Dec (deg)	Ang Err (deg)	
133572_82361476	IceCube-191231A	155.38	58849.46	46.36	20.42	1.72	
4FLG ASSOC			ASSOC	RA (deg)	Dec (deg)	Ang Sep (deg)	Type
4FGL J0258.1+2030			MG3 J025805+2029	44.54	20.51	1.71	bll
ID	GCN NAME	Energy (TeV)	MJD	RA (deg)	Dec (deg)	Ang Err (deg)	
133348_80807014	IceCube-191122A	128.44	58809.95	27.25	-0.04	1.82	
4FLG ASSOC			ASSOC	RA (deg)	Dec (deg)	Ang Sep (deg)	Type
4FGL J0148.6+0127			PMN J0148+0129	27.15	1.46	1.51	bll

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

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