Correlation of highly variable blazars with TeV IceCube track events

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ABSTRACT
The first ever identification of a cosmic ray accelerator as the consequence of spacial and temporal correlation of IceCube event 170922A with flaring of a blazar TXS 0506+056 motivated us to look for other flaring blazars in Fermi-LAT 3FGL catalog, which could be correlated with IceCube high energy track events. We have studied the Fermi-LAT light curves of blazars correlated with neutrino track events. We have calculated the multi-wavelength spectra and neutrino fluxes expected from these blazars with time dependent modelling of leptonic energy losses and proton-proton interactions in the jets of blazars. The expected fluxes are compared with observational results to determine whether the blazars could be the origin of the correlated neutrino events.

Key words: galaxies:active - galaxies:jets - gamma-rays:galaxies

1 INTRODUCTION

The origin of cosmic rays remains a mystery even after 100 years of their discovery. Highest energy cosmic rays are believed to be accelerated in extra-galactic astrophysical sources. High energy neutrinos are produced in or near these sources when cosmic rays interact with matter and ambient radiation. Unlike cosmic rays, these secondary neutrinos are neutral and very weakly interacting, as a result they travel through space undeflected from the direction of their sources to us. Therefore they are assumed to be smoking gun evidence for tracing origin of cosmic rays. Among different extra-galactic sources, blazars, a class of AGN with their powerful relativistic jets pointed towards us, are likely candidates for the sources of high energy cosmic rays.

IceCube neutrino telescope at the South Pole has detected many neutrino events of astrophysical origin over the last decade. On 22nd September, 2017 IceCube detected neutrino track-like event (IceCube-170922A) with energy > 290 TeV [1], which was coincident in direction and time with the γ-ray flare from a blazar TXS 0506+056. Subsequently a multi-wavelength campaign was followed involving telescopes across the globe. Most importantly high energy gamma ray flux $< 4.5\times10^{-11}$ cm^{-2} s^{-1} above energy 90 GeV was detected by MAGIC detector after stacking two epochs of observations one on Oct 3-4, 2017 and one on Oct 31, 2017 (??). IceCube collaboration analysed 9.5 years of data from the direction of TXS 0506+056 and found there was an excess of events above atmospheric background between September 2014 and March 2015 (?). These results indicate that blazars could be sources of astrophysical neutrinos. This correlation has been further analysed (?). The possibility of more such correlations has also been explored (?) recently.

A series of papers has been published to explain the multi-wavelength flare and the neutrino event from TXS 0506+056 by leptonic and photo-hadronic emission (????), and also proton-proton interactions (?????). Below, we discuss the results on theoretical modelling of TXS 0506+056 from a few of these papers. A time dependent modeling of multi-wavelength flare of TXS 0506+056 by synchrotron and synchrotron self Compton emission (SSC) has been done by (?) assuming the neutrino event is produced in photo-hadronic interactions. This scenario requires super-Eddington jet power to explain the neutrino event. X-ray emission constrains the photo-hadronic model of neutrino production. (?) considered synchroton and external Compton emission of relativistic electrons to explain the multi-wavelength spectrum of flare from TXS 0506+056 and radiatively subdominant hadronic emission to explain the neutrino event IceCube-170922A. In their model the ratio of luminosities in protons to electrons is large, $L_p/L_e \sim 250$ to 500.

Proton-proton interactions inside the jet, where the number of protons is determined from balancing the charge

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[1] https://gcn.gsfc.nasa.gov/gcn3/21916.gcn3

of electrons, can also explain the neutrino event IceCube-190722A (?).

Motivated with this, we look for further candidate variable blazar sources with the publicly available high energy IceCube neutrino track events. Our angular correlation study resulted correlation of eight flaring blazars. Out of which we found blazar 3FGLJ2255+2409 has an additional correlation of flaring state in gamma-rays with the IceCube neutrino event. We model the multi-wavelength spectra of 3FGLJ2255+2409 with time dependent leptonic model and proton-proton interactions in the emission region inside the jet to estimate the energy budget required to explain the emission.

2 ICECUBE TRACK EVENTS & FERMI-LAT VARIABLE SOURCES

IceCube has been detecting neutrinos of astrophysical origin since 2010. Most of these are shower-like events, which has on the average 15° angular uncertainties. Therefore it is very difficult to identify the sources of these neutrino events. The track events, on the other hand, are generated by muon type neutrinos (ν_μ) in charged current (CC) interaction, having on an average of 1° uncertainty in angular position. Hence for the analysis presented in this paper, we select all the track-like high energy events detected by IceCube from publicly available data .

High energy neutrinos are assumed to be smoking gun evidence for tracing their astrophysical origin. Recent discovery of cosmic neutrino events of energy 20 TeV to 2 PeV by the World's largest neutrino telescope the IceCube Neutrino Observatory, are the first astrophysical neutrinos ever detected (see **??**). The six year high energy starting events (HESE) include 82 events that include atmospheric muon background (25 ± 7.3) and atmospheric neutrino background ($15.6^{+11.4}_{-3.9}$). However finding the origin of these neutrino events is still a big challenge, particularly due to the large uncertainties in their arrival directions. The track events, generated by muon type neutrinos (ν_μ) with charge current (CC) neutrino-nucleon interactions have on an average 1° angular resolution whereas the shower events, resulted from electron and tau type neutrino-nucleon interactions (ν_e **and** $\nu_\tau - \mathbf{N}$) as well the $\nu_\mu - \mathbf{N}$ neutral current (NC) have an average angular resolution of 15°. Due to lesser angular uncertainty we have chosen the neutrino track events for our analysis. Out of the HESE 82 events 22 events are track events

More HESE and EHE events have been reported in recent past for real time analysis [2], we have included the tracks of these events for our analysis. Apart from these events we have included the six year up going muon track events that have been reported by IceCube above deposited energy 200 TeV (?). Out of the 29 such events 4 events have angular uncertainty more than 4 degrees, hence we have neglected these 4 events.

We have considered all the AGN (Active Galactic Nuclei) from 3FGL catalog (?) having variability index more than 100 as possible sources of the IceCube neutrino events. A source is identified as variable with 99% CL if its variability index is more than 71.44. 445 out of 1749 AGN have variability index more than 100. Figure **??** shows the skymap of the IceCube neutrino events with their 2σ angular uncertainty, along with the Fermi 3FGL AGN with variability index more than 100. We looked into Fermi 3FGL catalogue and selected blazars which are located within 2σ angular distance from these IceCube events.

We find 8 sources correlate within the 2σ angular uncertainty of the list of IceCube track events chosen. The statistical significance of this correlation is calculated using ?. We found a pre-p-value 0.0875. The correlated AGN are listed in table **??**.

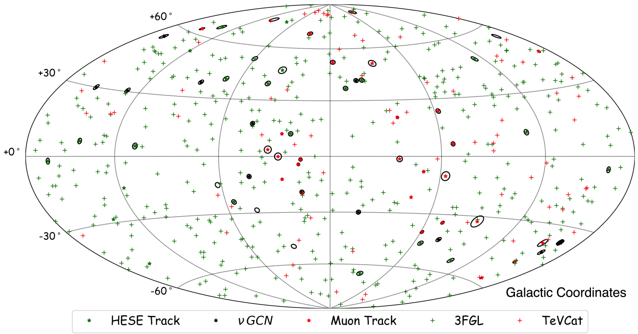

Figure 1. Skymap of all IceCube HESE and μ-track events along with blazars from 3FGL and TeV catalogue.

Name	Associated source	Var. index	Ang. dist.	MJD
J1848+3216	B2 1846+32A	273.125	0.12°	56859
J1040+0617	GB6 J1040+0617	124.921	0.27°	57000
J2255+2409	MG3 J225517+2409	103.265	1.21°	55355
J0823-2230	PKS 0823-223	121.623	1.56°	55387
J1310+3222	OP 313	556.442	1.00°	56062
J0509+0541	TXS 0506+056	285.297	0.59°	58018
J2254+1608	3C 454.3	60733.9	0.93°	57305
J0112+3207	4C +31.03	955.465	0.94°	57614

Table 1. List of blazars correlated with the IceCube track events within angular uncertainty of 2σ.

3 FERMI-LAT LIGHT CURVE ANALYSIS

The Fermi-LAT is a γ-ray telescope in space sensitive to photon energies greater than 20 MeV with a field of view of about 2.4 sr (?). The primary observation mode of Fermi-LAT is survey mode in which the LAT (Large Area Telescope) scans the entire sky every 3 hr. We analysed data for selected sources using Fermi Science Tools software package. In this analysis, we have considered photons of energy greater than 100 MeV.

We analysed all the 7 correlated sources [3] to look the

[2] https://gcn.gsfc.nasa.gov/amon_hese_events.html, https://gcn.gsfc.nasa.gov/amon_ehe_events.html

[3] we have excluded the TXS0506+056 source from further analysis, as a lot of work has already been done on the source.

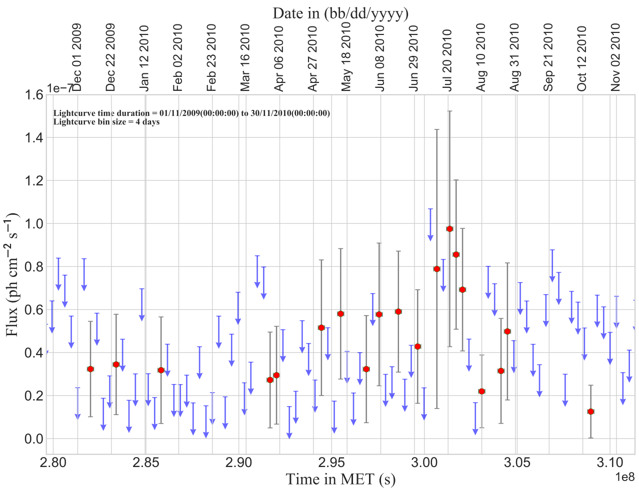

Figure 2. Lightcurve (ph/cm^2/s) for 3FGL J2255+2409 from 100 MeV to 300 GeV around ν-phase. a line for IceCube event day should be drawn and need to remove Date in (bb/dd/yyyy) need to be removed

light curve for two months within the IceCube neutrino track event and found no variability around the event except for 3FGL J2255+2409 Is it possible to give some quantitative answer to it? as shown in figure ??. Hence further we analysed the Fermi-LAT data as well the SED.

4 SPECTRAL ENERGY DISTRIBUTION

3FGLJ2255+2409 (associated source MG3 J225517+2409) is within the 2σ angular resolution of muon track event having most probable energy 339 TeV leading to most probable ν-event energy 442 TeV. This event was observed during IC79 configuration with signal probability 0.86 [4] (?).

For the SED modelling we collected the available observational data of MG3 J225517+2409 at radio frequency 1.4 GHz from NRAO VLA Sky Survey in 1998 (?) and the X-ray data taken by ROSAT (?). The X-ray data recorded by Swift and gamma-ray data recorded by Fermi-LAT have been analysed in this work.

4.1 Swift-XRT/UVOT Analysis

We analysed Swift-XRT/UVOT data for the source 3FGL J2255+2409 during the period overlapping with IceCube event. Details on the observations are presented in Table 2.

For this we retained cleaned event files using the task "xrtpipeline" version 0.13.2. Latest calibration files (CALDB version 20160609) and standard screening criteria were used for re-processing the raw data. Circular regions of radius 20 arcsec centered at the source and slightly away from the source were chosen for the source and the background respectively. Source was very faint in X-ray thus not visible.

Obs ID	Exp. Time (XRT)	Exp. Time (UVOT)	MJD
00041537001	1.1 ks	1.0 ks	55463.9
55463.9	0.5 ks	0.5 ks	55490.6

Table 2. Swift-XRT/UVOT analysis for 3FGLJ2255+2409.

Therefore we could not obtain spectra for this source. Ultraviolet/Optical Telescope used all six filters: U, V, B, W1, M2, and W2 to observe this source. The source image was extracted from a region of 5 arcsec centered at the source. The background region was chosen with a radius of 10 arcsec away from the source. The "uvot source" task has been used to extract the source magnitudes and fluxes. Magnitudes are corrected for galactic extinction (?) and converted into flux using the zero-points (?) and conversion factors (?).

4.2 Fermi-LAT γ rays with 4FGL configuration

We collected Fermi-LAT $\gamma-$ray data for three phases, a) pre ν-phase from November 2009 to April 2010 for six months b) ν-phase, May to July 2010, two months and c) post ν-phase, August 2010 to January 2011, another six months. To extract the spectral points we used the 4FGL configuration. Please change this line according to your convenience.

4.3 IceCube ν event.

The spectral point of the neutrino event is calculated using the exposure given in (?). The event was detected during the partial configuration IC79 corresponding neutrino energy 442 TeV at RA $=344.93^{+3.39}_{-2.90}$, Dec $= 23.58^{+0.91}_{-1.18}$ with 90% C.L.

4.4 SED modelling

The emission region is assumed to be a spherical blob of radius R moving with Doppler factor δ along the axis of the jet of the source. The injected spectrum of relativistic electrons at energy E'_e in the jet frame/comoving frame is, $\frac{dN_e}{dE'_e} \propto E_e'^{-\alpha}$. The synchrotron and synchrotron self Compton (SSC) photon spectra from these electrons are calculated using the publicly available GAMERA code [5]. The code solves the time depended transport equation and gives the radiation spectrum (?). Similarly, for the injected protons the spectrum at energy E'_p is, $\frac{dN_p}{dE'_p} \propto E_p'^{-\alpha}$. These protons are losing energy in hadronic interactions pp with the cold protons in the jet. We calculated the secondary high energy photon spectrum from pp interactions using SYBILL 2.1. We have calculated average neutrino flux as 2/3 of the gamma-rays produced produced in pp interactions following (?). Here we have taken the cold to hot proton density ratio as $\epsilon_p = 900$. The resulting high energy photons are attenuated due to pair production. We calculated the opacity and the resulting secondary electron, positron emissivity following the formalism discussed in ??. Using the spectrum of secondary electrons and positrons as the injection

[4] https://icecube.wisc.edu/icecube/static/science/HE_NuMu_data-table.pdf

[5] http://libgamera.github.io/GAMERA/

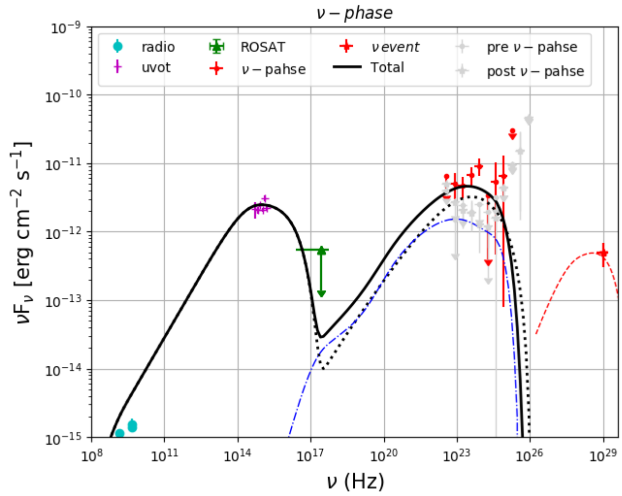

Figure 3. SED modelling of the ν-phase, between time period MJD55317 to MJD55407 of 3FGLJ2255+2409. The synchrotron and ssc modeling of the injected electron is shown with dotted line (black). The dashed (red) line shows the neutrino flux from pp interaction, while dot-dashed (blue) line represented the cascade photons from pp interaction. At the end the solid line (black) shows the total flux including the EBL correction.

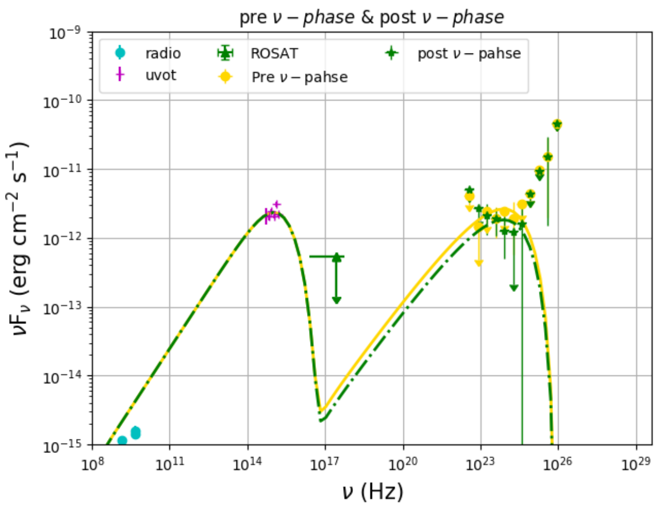

Figure 4. SED modelling of the pre ν-phase, within time period MJD55136 to MJD54951 with solid line (yellow) and the post ν-phase, within time period MJD55409 to MJD55592 with dot-dashed line (green) of 3FGLJ2255+2409.

spectrum, we calculated the cascade of photons using GAMERA. We have calculated photons from pion decay electron-positron pair from subsequent production of proton-proton interaction. For this we used the average production of electrons following (?). As the source has a tentative redshift of 1.37, we have taken EBL correction for redshift 1.37 from Franceschini-Rodighiero-Vaccari (FRV) model (?)[6].

[6] http://www.astro.unipd.it/background/

Parameters	pre ν-phase	ν-phase	post ν-phase
$\gamma_{e,min}$	6.5	-	-
$\gamma_{e,max}$	7.2×10^4	-	-
B [G]	0.04	0.18	0.04
α_e	1.85	1.78	1.85
Radius[cm]	3.2×10^{17}	5×10^{16}	2.5×10^{17}
δ	21	26.5	21
L_e **[erg/sec]**	1.12×10^{42}	9×10^{41}	1.12×10^{42}
Hadrons	-	-	
$\gamma_{p,min}$	10	-	-
$\gamma_{p,max}$	1000	-	-
α_p	-	1.78	-
L_p^{hot} **[erg/sec]**	-	7.9×10^{43}	-
n_H^{cold} **[cm^{-3}]**	-	1466.28	-
$N_{\nu,tot}$	-	1.012	-
L_j **[erg/sec]**	8.03×10^{44}	$\mathbf{3.6 \times 10^{47}}$	8.4×10^{44}

Table 3. SED modeling parameters

5 RESULTS AND DISCUSSION

We studied the angular correlation of variable AGN sources from 3FGL catalogue with the IceCube TeV-PeV track events. The result showed 8 candidate sources within 2σ angular uncertainties, including TXS 0506+056. Out of the 7 candidate sources, we found a spacial as well temporal correlation of a flare from 3FGL J2255+2409 with a 340 TeV muon track event in IceCube 79 string configuration.

We have modeled 3FGL J2255+2409for for all the three phases, pre ν-phase, post ν-phase with time dependent leptonic model and the ν-phase with time dependent leptonic as well time independent hardronic model using proton-proton (PP) interaction.

The jet luminosity for the pre and post ν-phase are $L_j = 8.03 \times 10^{44}$ and 8.4×10^{44} with a blob radius $R' = 3.2 \times 10^{17}$ The total jet luminosity during ν-phase is $L_j = 3.6 \times 10^{47}$ erg/sec for our lepto-hadronic model, while the Eddington luminosity $L_{Edd} = 1.2 \times 10^{47}$ erg/sec for a black hole mass 10^9 $M_\odot$. We found the neutrino event number as 1.012 for the IC79 configuration from our lepto-hadronic model in the ν-phase.

To the best of our knowledge this is the first time the Fermi-LAT 3FGL source, 3FGLJ2255+2409/MG3 J225517+2409 has been analysed as the source of IC79 track event. please see if we can add the ANTARES result here. IceCube has been looking for point sources with the eight year track events (?). This analysis can also be used to investigating stringent evidences of 3FGLJ2255+2409 being source of TeV-PeV neutrino events.