Active Galactic Nuclei as sources of the diffuse neutrino background

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Abstract: The detection of a high-energy (∼290 TeV) neutrino, IceCube-170922A, by IceCube on September 22, 2017 was in directional and temporal coincidence with the blazar TXS0506+056. The discovery of this first neutrino source indicates that blazars are possible sources of high-energy neutrinos. Blazars are active galactic nuclei with the relativistic jet pointing towards the Earth. Neutrino production occurs in the jet because of hadronic processes. Since IceCube has previously detected a diffuse high-energy neutrino background, we try to model the contribution of the blazar population to it. Blazars are classified into two types, BL Lac objects and FSRQs. We study the neutrino flux of the population of each class of blazars separately, considering that all sources emit as TXS0506+056, with a lepto-hadronic modelling neutrino flux, and assuming the number density of BL Lacs and FSRQs derived from the Fermi Large Area Telescope data, respectively. The diffuse emission of the BL Lac objects fits in with the IceCube data, while the FSRQs' one is much higher than the observed neutrino flux. This can be explained if the neutrino production in FSRQs is somehow suppressed, suggesting an intrinsic difference between the two blazar subclasses. Furthermore, we study the cosmic ray diffuse emission of the BL Lac objects and we conclude that only a small fraction of protons can escape efficiently from the relativistic jet of the blazars.

I. INTRODUCTION

Neutrinos are tracers of high-energy cosmic ray acceleration in the Universe, being able to escape from the densest astrophysical environments, where photons cannot. When the protons and nuclei are accelerated, they interact with the gas and photons around them and produce subatomic particles, such as pions and kaons, which rapidly decay emitting neutrinos, together with photons, electrons and positrons. The new multimessenger era of astrophysical observations has started, since now we can detect neutrinos and also gravitational waves, in addition to the classical photon observation.

The existence of astrophysical neutrinos was first confirmed by Kamiokande II and IMB observatory, who detected in 1987 cosmic neutrinos in correlation with a supernova located inside the Large Magellanic Cloud [12, 18]. Many neutrino detectors have been constructed since then, and we can distinguish three types of detectors by their location: underwater, underground and under ice. The Kamiokande observatory we mentioned above is an example of underground detector, installed in Japan.

In this work, we use the data from an under-ice detector, the IceCube neutrino Observatory. In 2013, IceCube discovered the existence of a diffuse flux of high-energy neutrinos extending above several PeV. And on September 22, 2017, they detected the neutrino IceCube-170922A, of $E \sim 290$ TeV, in correlation with the γ-ray blazar TXS0506+056 in flaring state, since gamma rays and other wavelengths were also recorded. This spatial and temporal coincidence suggests that blazars are a source of high-energy neutrinos, and thus of cosmic rays (CR).

The neutrinos that we can detect on the Earth's surface come from a lot of different types of sources. The nearest come from the Earth's atmosphere, as product of the interaction of the cosmic rays with the particles in the atmosphere, these are called the atmospheric background neutrinos and their energy is considered to be below 100 TeV [2]. An important portion of the relatively low energetic neutrinos comes from the fusion processes that take place in the Sun. These neutrinos have energies between 0.1 MeV and 20 MeV [5]. Another powerful MeV neutrino sources are the supernova explosions, that in the process of converting protons to neutrons release very large amount of neutrinos [19].

High-energy cosmic neutrinos come from other sources further away. These form the so called diffuse neutrino background and their energy goes from 100 TeV to a few PeV [2]. Possible sources of cosmic neutrinos are: gamma-ray bursts with an estimated contribution of a few percent [3], starburst galaxies also with a constrained contribution [11], the cores of galactic nuclei (AGNs) that includes the blazars, with a contribution of around 20% [1], the dark matter decay [15] and the galactic plane, with ∼10% contribution [8].

Blazars are a subclass of AGNs, which are compact regions at the center of a galaxy with very high luminosity. This high radiation is believed to result from the accretion of matter onto a supermassive black hole, launching relativistic jets and emitting nonthermal radiation. This theoretical paradigm has been confirmed in 2019 by the first image of the supermassive black hole in M87 [27]. The AGNs that have the jet pointing nearly towards the Earth are called blazars.

We can distinguish two subpopulation of blazars: Flat-Spectrum Radio Quasars (FSRQs) and BL Lacertae (BL

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Lac) objects. The difference between them is that FSRQs are characterised by having strong emission lines in the optical spectrum, while there are no emission lines in BL Lac objects [23]. This dichotomy is thought to be linked to two different accretion regimes at work.

The overall spectral energy distribution (SED) of blazars exhibit two broad humps peaking in the IR–X–ray band and in the MeV–TeV band [17]. Another classification of blazars is based on the source frame frequency of the IR–X–ray band peak (ν^s_{peak}). In this way, low-energy peaked (LBL) sources are those with $\nu^s_{peak} < 10^{14}$ Hz [< 0.41 eV], intermediate-energy peaked (IBL) sources with $10^{14} < \nu^s_{peak} < 10^{15}$ Hz [0.41 eV − 4.1 eV], and high-energy peaked (HBL) sources with $\nu^s_{peak} > 10^{15}$ Hz [> 4.1 eV] [4, 23].

BL Lac objects are characterized by the so-called blazar sequence, that is the relation between the luminosity of a blazar and the photon spectrum emitted; as the bolometric luminosity L_{bol} increases, the ν^s_{peak} becomes lower. But FSRQs don't show the same behaviour, being all characterized by a low ν^s_{peak} [17]. Our source in question, TXS0506+056, was considered as a BL Lac object and a luminous HBL, but its L_{bol} and ν^s_{peak} suggest that it could be a masquerading BL Lac, i.e., intrinsically a FSRQ, with hidden emission lines [24]. Since the nature of this source is unclear, we take into account the two possibilities and then we compare the results with IceCube data [2].

The origin of the two humps in the SED is still under debate. In leptonic models, the low-energy bump is related to the synchrotron photons emitted by accelerating electrons, and the high-energy bump is supposed to be inverse Compton, in which low-energy photons are scattered to higher energies by relativistic electrons [13]. As an alternative to leptonic models, high-energy hadronic processes in relativistic jets produce particles that decays into neutrinos. The main process is the interaction of the proton or neutron population with the low-energy photons through photomeson processes producing π^0 and $\pi^\pm$ [22]. Then the pions decay into neutrinos and leptons.

Once IceCube-170922A has been detected, several authors [10, 14, 16, 21] have proposed consistent models for the electromagnetic and neutrino emission of TXS0506+056 assuming a lepto-hadronic model for the jet of the blazar. In this work, we use the neutrino flux computed by [14], using the lower and the upper limits of their results.

Since several models of photon and neutrino emission of TXS0506+056 have been proposed, one may ask if these models are consistent with the observed diffuse neutrino background. This work tries to answer this question and estimate the contribution of blazars to it. And finally we analyse the implication of our results to the AGN physics.

Given that the presence of neutrinos and protons in the jets are linked, we can also study the contribution of blazars to the cosmic ray flux. Cosmic rays are charged particles dominated by protons, and as the neutrinos we don't know their origin, but thanks to the detection of photons and neutrinos possible sources are considered, since the emission of photons and neutrinos implies the presence of hadrons in the source. For simplicity we only consider protons and that they are not substantially deviated in their trajectory to the Each by the magnetic fields. An escape rate is considered to take into account that not all the protons that are accelerated in the jet can escape without losing energy, then we can compare the results with Tibet III and Auger's data [9, 25].

In the following sections we explain the process to compute the neutrino diffuse emission (section II) and the cosmic ray diffuse emission (section III). In the section IV we present and discuss the results, and in section V we state our conclusion.

II. DIFFUSE EMISSION OF NEUTRINOS FROM BLAZARS

To compute the diffuse neutrino flux we assume that all the population of blazars radiates in the same way as our source, i.e. with the same distribution of neutrino flux. In the first case, we consider that the TXS0506+056 is a bright HBL, and we compute the contribution of the population of HBLs in the neutrino diffuse emission. Then, we consider the source as a FSRQ to obtain the contribution of the population of FSRQs.

The cumulative diffuse emission is determined following [26]. Q and Q' indicates quantities measured in the observer and source frame, respectively:

$$E_\nu I(E_\nu) = \frac{c}{4\pi H_0} E_\nu^2 \int \frac{j(E_\nu(1+z), z)}{\sqrt{\Omega_M(1+z)^3 + \Omega_\Lambda}} dz, \qquad (1)$$

where $j(E_\nu(1+z), z)$ is the comoving volume neutrino emissivity as function of the energy E_ν and the redshift z. We assume the Hubble constant $H_0 = 70$ km s^{-1} Mpc^{-1} and the constants of cosmology $\Omega_M = 0.3$ and $\Omega_\Lambda = 0.7$. We calculate the comoving volume neutrino emissivity as the product of the comoving density of sources $\Sigma(z)$ and the source neutrino luminosity for a blazar

$$j(E_\nu(1+z), z) = \Sigma(z) \frac{L_\nu(E_\nu(1+z))}{E_\nu(1+z)}, \qquad (2)$$

The comoving density of BL Lac objects has been studied by [6], and for simplicity, we made the same parametrization as [26], focusing on HBL evolution:

$$\Sigma_{BLLac}(z) = \Sigma_0(1+z)^{-6}, \qquad (3)$$

where $\Sigma_0 \simeq 2\times10^{-7} Mpc^{-3}$. Notice that, local HBL have a negative evolution since the comoving density decreases with z. On the other hand, for FSRQs [7], the comoving density increases for $z \leq 0.6$ and then decreases with a smoother rate than HBLs do, hence the $\Sigma_{FSRQ}(z)$ is parametrized with a piecewise function:

$$\Sigma_{FSRQ}(z) = \begin{cases} (Az^3 + Bz^2 + Cz + D), & \text{if } z \leq 0.6, \\ \Sigma_0(1+z)^{-4}, & \text{if } z \geq 0.6. \end{cases} \tag{4}$$

in this case, $\Sigma_0 \simeq 2 \times 10^{-8} Mpc^{-3}$, $A \simeq -3 \times 10^{-8} Mpc^{-3}$, $B \simeq 2 \times 10^{-8} Mpc^{-3}$, $C \simeq 2 \times 10^{-9} Mpc^{-3}$ and $D \simeq 5 \times 10^{-10}\ Mpc^{-3}$

From [14] we have the neutrino flux for TXS0506+056 as a function of the frequency in the observer frame, $F_\nu(\nu)$, and we use this to calculate the luminosity $L_\nu(E'_\nu)$. With the luminosity of this source, we can derive the diffuse intensity of neutrinos $I_\nu(E'_\nu)$ as function of the neutrino's energy, for the considered population of blazars (BL Lacs or FSRQs). The energy is given by $E_\nu = h\nu$, where h is the Planck constant and ν' is related to the ν frequency in the observer frame by $\nu' = (1+z)\nu$, where $z = 0.337$ is the redshift of the source. To obtain the neutrino's luminosity, we can use the relation

$$L_\nu(\nu') = 4\pi d^2 F_\nu(\nu') \tag{5}$$

where $d = 5.848 \times 10^9$ light year is the luminosity distance of the source for the cosmological parameters given above.

Once we obtain the luminosity $L_\nu(\nu')$, we can compute the emissivity $j(E_\nu, \nu)$ for the two cases: assuming the source as a BL Lac object, multiplying by $\Sigma_{BLLac}(z)$, and assuming the source as a FSRQ, multiplying by $\Sigma_{FSRQ}(z)$. Then we proceed to compute the integral in the equation 1 using Gauss-Legendre Quadrature method. The limits of the integral are $z = 0$ to $z = 3.3$ for HBLs, and $z = 0$ to $z = 4.8$ for FSRQs. Given the very steep functions, the result is not sensitive to the high limit of the integral.

Some corrections are needed since the flux we consider is of a blazar in flaring state, i.e. when the emission is extraordinarily strong and, on the other hand, as we said before, this source is a "blazar sequence" outlier since its luminosity is much larger than a typical HBL, with the same ν^s_{peak}.

To correct for the first consideration, we compute the average emission of gamma radiation of the source making use of the Fermi-LAT data, and we compare it with the flaring state gamma ray emission. We assume that the radiative mechanism during the flare is similar to the one during the non-flaring state, and thus that the gamma-ray to the neutrino flux ratio remains constant. Hence, the neutrino intensity of TXS0506+056 in a non-flaring state is

$$\text{Corrected}\, E_\nu I_\nu(\nu) = E_\nu I_\nu(\nu) \times \frac{\text{Average } \gamma\text{-ray flux}}{\text{Flaring state } \gamma\text{-ray flux}}$$

as we can observe in the FIG 1, the Average γ-ray flux $\simeq$ 2.36×10^{-7} cm^{-2} s^{-1}, and the Flaring state γ-ray flux $\simeq$ 4.42×10^{-7} cm^{-2} s^{-1}; so the correction is about $\sim$0.5.

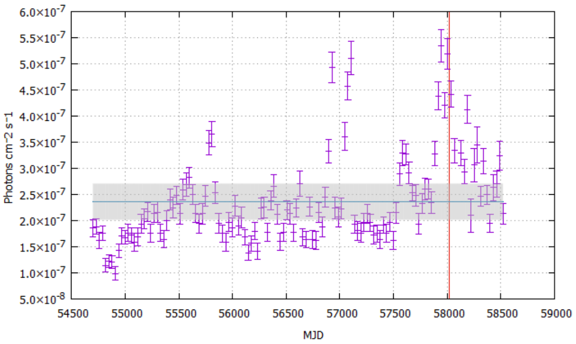

FIG. 1: Fermi LAT data of γ-rays for the source TXS0506+056 per Modified Julian Date (MJD). The average is the green line computed with the uncertainty represented by the gray band. The neutrino IceCube-170922A has been detected on MJD = 58018.

Finally, for the second consideration, only needed for BL Lacs, we assume that our source is much brighter than typical HBLs, and from the Figure 1 given by [24], we see that there is a factor $\sim 10^3$.

The results of the diffuse neutrino emission are showed in the FIG 2. We can observe that the BL Lac model band is consistent with the upper limits recorded by IceCube, whereas the FSRQ model curve give an overly large intensity.

III. COSMIC RAY DIFFUSE EMISSION FROM BLAZARS

As the blazar jets emit protons, ions, electrons, neutrinos and other particles at a very high energy, we can study its contribution to the diffuse CR emission. In this work, for simplicity, we assume that all CR are protons, and in a first approach, we make the assumption that all the protons can escape efficiently from the jet and are not deviated by magnetic fields. We compare the modelling results with the Tibet III [9] and Auger [25] data.

The diffuse CR emission intensity is computed with a similar calculation as for neutrino diffuse intensity, thus, we need the proton's flux as function of frequency in the comoving frame. [14] have calculated the differential density of the protons as function of Lorentz factor, $n(\gamma')$. Given the relation between energy and Lorentz factor

$$\gamma' = \frac{E'}{m_p c^2} \tag{6}$$

where m_p is the proton's mass and c is the speed of light, we switch to the observer frame with

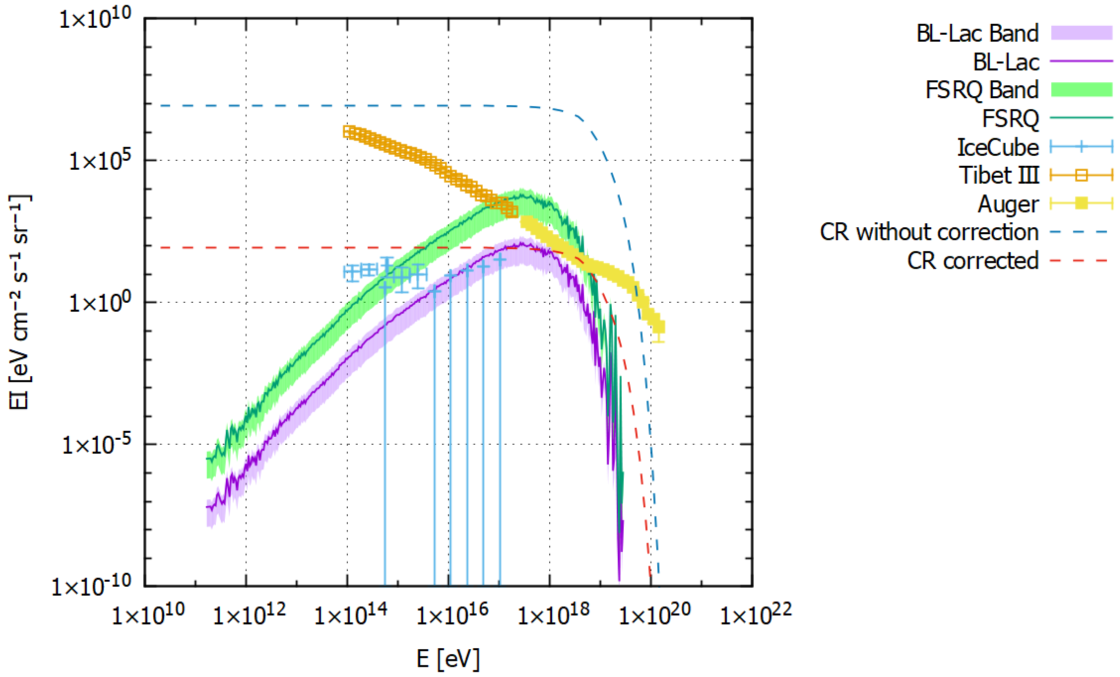

FIG. 2: Diffuse neutrino emission intensity considering the population of HBLs in purple solid line, and the one considering the population of FSRQ in green line, with their respective bands corresponding to the upper and lower limits of the neutrino flux computed by [14]. IceCube data are in blue, the long bars reaching zero are upper limits. Uncorrected diffuse CR emission intensity is the blue dashed line, and the corrected one is the orange dashed line. Tibet III data of CR are in orange and Auger data of higher energy CR are in yellow.

$$E = \frac{\delta_b}{1+z} E' = \frac{\delta_b}{1+z} m_p c^2 \gamma'. \tag{7}$$

And, the Lorentz factor in the observer frame is

$$\gamma = \frac{E}{m_p c^2}. \tag{8}$$

The number density of particles per energy interval, i.e. the differential density is described by [20].

$$n(\gamma) = \frac{3}{4}\frac{4\pi}{hc\gamma'}\frac{j'(E')}{k'(E')}(1 - exp(-k'(E')R_b)). \tag{9}$$

where $j'(E')$ is the emission coefficient, $k'(E')$ is the absorption coefficient and R_b is the radius of the emitting region. We assume for our source that the correction $exp(-k'(E')R_b) \sim 0$, and then, the absorption coefficient $k'(E') \simeq \frac{1}{R_b}$, thus

$$j'(E') = \frac{hc}{3\pi}\frac{n(\gamma)}{R_b}\gamma' \tag{10}$$

The intensity in the source frame is given by

$$I'(E') = j'(E')R_b = \frac{hc}{3\pi} n(\gamma)\gamma' \tag{11}$$

The emitting blob in the blazar jet has a relativistic motion to the observer, which produce a Doppler boosting effect. Hence, the flux density that we observe is given by

$$F(E') = \pi \frac{R_b^2}{d^2} \delta_b^3 (1+z) I'(E') \tag{12}$$

where $\delta_b = 30$ is the Doppler factor assumed in the modelling. Then we proceed to calculate the diffuse intensity using the equations of the Section II. We consider the diffuse CR emission for HBLs only, since we have obtained that, for the FSRQ's model, the result of the diffuse neutrino emission doesn't fit to the IceCube data. Computed diffuse CR emissions are represented in the FIG 2. We first study the case where all CR can escape jet without loosing energy (non-corrected CR flux), and then introduce an escape rate (corrected CR flux).

IV. RESULTS

The diffuse neutrino emission for the BL Lac model is compatible with the upper limits of IceCube data. In the FIG 2 we see that the emission peaks at $\sim 10^2$ PeV. The emission band is consistent with the observed diffuse neutrino flux, and we note that at energy of ~1 PeV, the BL Lacs' contribution is of ~10%, in agreement with [1]. Therefore, this shows that the diffuse astrophysical neutrino flux at the $> PeV$ energies may be due to BL Lac objects, although they only provide a small contribution to the sub-PeV neutrino flux.

On the other hand, the diffuse neutrino flux in the FSRQ model is approximately 2 order of magnitudes higher than the one observed by IceCube. It means that, if all FSRQs emit a similar neutrino flux as TXS0506+056, IceCube would have already detected them.

Regarding the cosmic ray emission with an escape rate = 1 (the non-corrected flux) the intensity is extremely larger than the observed one, so we introduce an escape rate of 10^{-5} in the corrected CR flux. This indicates that the vast portion of the protons can't escape from the jet without losing energy. The strongest contribution by HBLs in this case is to the CR at $\sim 10^4$ PeV.

V. CONCLUSIONS

Blazars produce neutrinos by hadronic processes in the relativistic jet and these high-energy neutrinos can escape efficiently because of their low interaction rate. We study the diffuse astrophysical neutrino flux that would produce the population of the two types of blazars, BL Lac objects and FSRQs, assuming that all these sources emit as the first high-energy neutrino source detected by IceCube, TXS0506+056. In addition, we study the cosmic ray emission of the population of BL Lac objects.

We observe that the neutrino emission peaks at $\sim 10^2$ PeV with a ~10% contribution to the 1 PeV neutrinos, in the case of the BL Lac model. And that the cosmic ray emission is suitable if the escape rate is 10^{-5}. The conclusion which can be derived for FSRQs is that these have to provide a neutrino flux significantly smaller than the one measured from TXS0506+056. This could be explained if jets from FSRQs and BL Lac objects are intrinsically different and CR acceleration is somehow suppressed in FSRQs.

In this work we analysed the diffuse neutrino flux from all non-flaring blazars. The next step is to study the impact of flaring blazars taking into account their duty cycle, that is, how many flares per ~10 years during the IceCube time exposure are needed to reproduce the neutrino diffuse emission.

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