Describing correlated observations of neutrinos and gamma-ray flares from the blazar TXS 0506+056 with a proton blazar model

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Recent detection of the neutrino event IceCube-170922A by the IceCube Observatory from the blazar TXS 0506 + 056 in the state of enhanced gamma-ray emission indicates the acceleration of cosmic rays in the blazar jet. The nondetection of the broadline emission in the optical spectrum of TXS 0506 + 056 and other BL Lac objects suggests that external photon emissions are weak, and hence, photo-meson ($p\gamma$) interaction may not be a favored mechanism for high-energy neutrino production. The lack of broadline signatures also creates doubt about the presence of a high density cloud in the vicinity of the supermassive black hole of TXS 0506 + 056 and consequently raised question on hadronuclear (pp) interaction interpretation like relativistic jet meets with high density cloud. Here we demonstrate that nonrelativistic protons in the proton blazar model—those that come into existence under the charge neutrality condition of the blazar jet—offer sufficient target matter for pp interaction with shock-accelerated protons, and consequently, the model can describe consistently the observed high-energy gamma rays and neutrino signal from the blazar TXS 0506 + 056.

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I. INTRODUCTION

Very recently, the IceCube Neutrino Observatory reported the detection of a high-energy muon-neutrino event IceCube-170922A of energy ~290 TeV with a 56.5% probability of being a truly astrophysical neutrino [1,2]. The best-fit reconstructed arrival direction of the neutrino was consistent with the 0.1^0 from the sky location of the flaring gamma-ray blazar TXS 0506 + 056 [1,3]. As a follow-up observation, the Fermi Large Area Telescope (LAT) Collaboration [4] reported that the direction of the origin of IceCube-170922A was consistent with the known gamma-ray source TXS 0506 + 056 blazar, which was in a state of enhanced emission with day-scale variability [5] on September 28, 2017. The observed association of a high-energy neutrino with a blazar during a period of enhanced gamma-ray emission suggests that blazars may indeed be one of the long-sought sources of very-high-energy cosmic rays, and hence, these observations offer a unique possibility to explore the interrelation between energetic gamma rays, neutrinos, and cosmic rays.

The electromagnetic spectral energy distribution (SED) of the blazar TXS 0506 + 056 exhibits a double-hump structure which is a common feature of the nonthermal emission from blazars. The first hump, which peaks in the optical-ultraviolet range, is usually attributed to synchrotron radiation, and the higher-energy hump with peak energy in the GeV range is often interpreted due to inverse-Compton (IC) emission. An archival study of the time-dependent γ-ray data over the last ten years or so reveals that the source was in a quiescent stage most of the time, and the flaring was noticed during the period July 2017 to September 2017. The average integrated flux above 0.1 GeV from TXS 0506 + 056 was found to be $(7.6 \pm 0.2) \times 10^{-8}$ cm^{-2} s^{-1} from 2008 to 2017 from Fermi-LAT observations, which in week 4 to July 11, 2017 elevated to the level $(5.3 \pm 0.6) \times 10^{-7}$ cm^{-2} s^{-1}. The Astrorivelatore Gamma a Immagini Leggero gamma-ray telescope obtained flux of $(5.3 \pm 2.1) \times 10^{-7}$ cm^{-2} s^{-1} from September 10 to 23, 2017. The Major Atmospheric Gamma Imaging Cherenkov (MAGIC) Telescopes detected a significant very-high-energy γ-ray signal with observed energies up to about 400 GeV on September 28, 2017. Note that the IceCube Observatory detected the neutrino event on September 22, 2017. It was found from optical to x-ray observations that the lower-energy hump of the SED of the source did not show any noticeable time variation over the stated period of study.

Several efforts have been made so far to model the production of the detected neutrino event together with the electromagnetic (EM) observations from TXS 0506 + 056. Mainly, two different production scenarios, namely, leptohadronic ($p\gamma$) [3,5–7] and hadronic (pp) [8,9] have been

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proposed in the literature to interpret the observations. A common feature of all the proposed models is that protons, like electrons, are also assumed to be accelerated to relativistic energies in the acceleration sites. Subsequently, the accelerated protons interacting with low-energy photons of the blazar environment (leptohadronic interaction) and/or with ambient matter produce high-energy gamma rays and neutrinos.

Ansoldi *et al.* [3] showed that the measured neutrino event from the said blazar can be interpreted consistently with the EM observations by assuming a dense field of external low-energy photons originating outside of the jet as targets for photohadronic interactions. The lack of broadline signatures in the optical spectrum of TXS $0506+056$ and other BL Lac objects suggests that such external photon emissions may be weak [5]. The model discussed in Ansoldi *et al.* [3], however, does not invoke radiation from broadlines, but instead, assumes the existence of soft radiation produced in a possible layer surrounding the jet. Therefore, the lack of broadlines does not impact this specific scenario. In this context, it is also to be noted that the BL Lac nature of TXS $0506+056$ has been recently questioned by Padovani *et al.* [10]. Keivani *et al.* [5] considered a hybrid leptonic scenario of TXS $0506+056$ where the production of high-energy gamma rays was interpreted by external inverse-Compton processes and high-energy neutrinos via a radiatively subdominant hadronic component.

For efficient high-energy γ-ray production in an active galactic nuclei (AGN) jet via pp interaction demands high thermal plasma density; the thermal plasma in the jet should exceed 10^6 cm^{-3} in order to interpret the reported TeV flares of Markarian 501 by pp interactions for any reasonable acceleration power of protons $L_p \leq 10^{45}$ erg/s [11]. The stated pure hadronic mechanism can thus be effectively realized in a scenario like the "relativistic jet meets target" [12], i.e., considering that γ radiation is produced in dense gas clouds that move across the jet [13]. Recently, Liu *et al.* [8] described the observed gamma-ray and neutrino flux from the blazar TXS $0506+056$ by assuming the presence of clouds in the vicinity of the supermassive black hole (SMBH) that provides targets for inelastic pp collisions once they enter the jet. Liu *et al.* considered the synchrotron emission and inverse-Compton emission of secondary electrons produced in a cascade when high-energy γ rays are absorbed in $\gamma\gamma$ pair production with the emission region of the jet. However, the presence of broadline region (BLR) clouds in the vicinity of the SMBH for TXS $0506+056$ is questionable due to the nondetection of the BLR emission from TXS $0506+056$ and other BL Lac objects [5].

The composition of the bulk of the jet medium is not clearly known, which makes it difficult to understand the interaction mechanism for gamma-ray and neutrino production. But on average, jet plasma must be neutral to remain collimated [14]. Therefore, two main scenarios for their matter composition are suggested: a "pair plasma" consisting of only relativistic electrons and positrons [15] and a "normal plasma" consisting of (relativistic or nonrelativistic) protons and relativistic electrons [16]. A useful quantity that can furnish some constraints on jet composition is the kinetic power of an AGN jet. By comparing the bulk kinetic energy of the parsec-scale jet with the kinetic luminosities on extended scales [17], Celotti and Fabian [16] argued in favor of an electron-proton fluid. For high luminous blazars to maintain the radiated power which would not exceed that carried by the jet, the proton component of plasma is necessary (see Ghisellini *et al.* [18] and references therein).

In this context, in the present work we exploit the main essence of the proton blazar model [19,20] to explain the observed higher-energy bump of the EM SED along with the neutrino from the blazar TXS $0506+056$ at the flaring stage. The detected lower-energy bump of EM SED from the blazar can be well interpreted with the synchrotron radiation of relativistic electrons present in jet plasma, whereas the cold (nonrelativistic) proton density that arose from the charge neutrality condition can provide sufficient target matter (proton) for the production of high-energy gamma rays and neutrinos via the pp interaction. For TXS $0506+056$, such a scenario is more realistic than the scenario of the cloud-in-jet model [21] as we argue later. We would also like to examine the maximum energy that a cosmic ray particle can attain in the blazar jet; the detected ~290 TeV energy neutrino alone suggests that protons in the jet of this object are accelerated to energies of at least several PeV.

The organization of this paper is as follows: In the next section, we shall describe the methodology for evaluating the gamma-ray and neutrino fluxes generated in the interaction of cosmic rays with ambient matter in the AGN jet under the framework of the proton blazar model. The numerical results of the hadronically produced gamma-ray and neutrino fluxes from the AGN jet over the GeV to TeV energy range are shown in Sec. III. The findings are compared with the observed gamma-ray spectra and the neutrino event from the blazar, and the results are discussed in the same section. Finally, we conclude in Sec. IV.

II. METHODOLOGY

The overall jet composition of AGN is not properly known. In the adopted proton-blazar-inspired model, it is assumed that the relativistic jet material is composed of relativistic protons (p) and electrons (e). Some cold protons also exist, allowing charge neutrality to be fulfilled. The ratio of the number of relativistic protons to electrons, the maximum energies attained by protons/electrons in the acceleration process and the slope of their energy spectrum, luminosities of electrons and protons are adjustable parameters of the model. In this model, flaring is produced due to high magnetic activities in the source (similar to the origin of flaring activities in the Sun).

We consider a spherical blob of size R'_b (primed variables for the jet frame) in the AGN jet which is the region responsible for the blazar emission. The blob is moving with a Doppler factor $\delta = \Gamma_j^{-1}(1-\beta_j \cos\theta)^{-1}$ where θ is the angle between the line of sight and the jet axis, and $\Gamma_j = 1/\sqrt{1-\beta_j^2}$ is the bulk Lorentz factor [22], and it contains a tangled magnetic field of strength B'.

In the proton blazar framework, the low-energy bump of the SED is explained by synchrotron radiation of an accelerated relativistic electron in the blazar jet having a broken power law energy distribution as [23]

$$N'_e(\gamma'_e) = K_e \gamma_e'^{-\alpha_1} \quad \text{if } \gamma'_{e,\min} \le \gamma'_e \le \gamma'_b$$
$$= K_e \gamma_b'^{\alpha_2-\alpha_1} \gamma_e'^{-\alpha_2} \quad \text{if } \gamma'_b < \gamma'_e \le \gamma'_{e,\max}, \quad (1)$$

where $\gamma'_e = E'_e/m_e c^2$ is the Lorentz factor of electrons of energy E'_e, and α_1 and α_2 are the spectral indices before and after the spectral break Lorentz factor γ'_b, respectively. The normalization constant K_e can be found from [24]

$$L'_e = \pi R_b'^2 \beta_j c \int_{\gamma'_{e,\min}}^{\gamma'_{e,\max}} m_e c^2 \gamma'_e N'_e(\gamma'_e) d\gamma'_e, \quad (2)$$

where L'_e is the kinetic power in relativistic electrons in the blazar jet frame. The number density of highly relativistic ("hot") electrons is $n'_{e,h} = \int N'_e(\gamma'_e) d\gamma'_e$, and the corresponding energy density is $u'_e = 3p'_e = \int m_e c^2 \gamma'_e N'_e(\gamma'_e) d\gamma'_e$ where p'_e is the radiation pressure due to relativistic electrons. Because of the strong synchrotron and inverse-Compton cooling at relativistic energies, the acceleration efficiency of electrons in the AGN jet is quite low, and it can be assumed to be $\chi_e \approx 10^{-3}$ [25–27]. Hence, the total number can be determined as $n'_e = n'_{e,h}/\chi_e$. Thus, the number density of nonrelativistic ("cold") electrons is given by $n'_{e,c} = n'_e - n'_{e,h}$.

The emissivity of photons of energy E'_s $(= m_e c^2 \epsilon'_s)$ due to the synchrotron emission of electrons which describe the low-energy component of the EM SED of the blazar can be written as [24]

$$Q'_s(\epsilon'_s) = A_0 \epsilon_s'^{-3/2} \int_1^{\infty} d\gamma'_e N'_e(\gamma'_e) \gamma_e'^{-2/3} e^{-\epsilon'_s/(b\gamma_e'^2)} \quad (3)$$

with the normalization constant

$$A_0 = \frac{c\sigma_T B'^2}{6\pi m_e c^2 \Gamma(4/3) b^{4/3}},$$

where σ_T is the Thomson cross section, $b = B'/B_{\text{crit}}$, and $B_{\text{crit}} = 4.4 \times 10^{13}$ G. The magnetic field energy density is $u'_B = B'^2/8\pi = 3p'_B$ where p'_B is the corresponding pressure.

The emissivity of photons of energy E'_c $(= m_e c^2 \epsilon'_c)$ due to the inverse-Compton scattering of primary accelerated electrons with the seed photons comoving with the AGN jet, which can describe the lower part of the high-energy component of the EM SED of the blazar, can be written as [28,29]

$$Q'_c(\epsilon'_c) = \int_0^{\infty} d\epsilon'_j n'_j(\epsilon'_j) \int_{\gamma'_{e,0}}^{\gamma'_{e,\max}} d\gamma'_e N'_e(\gamma'_e) C(\epsilon'_c, \gamma'_e, \epsilon'_j), \quad (4)$$

where $\gamma'_{e,0} = \frac{1}{2}\epsilon'_c\left(1+\sqrt{1+\frac{1}{\epsilon'_c\epsilon'_j}}\right)$, and the Compton kernel $C(\epsilon'_c, \gamma'_e, \epsilon'_j)$ is given by Jones [30] as

$$C(\epsilon'_c, \gamma'_e, \epsilon'_j) = \frac{2\pi r_e^2 c}{\gamma_e'^2 \epsilon'_j}\left[2k\ln(k) + (1+2k)(1-k) + \frac{(4\epsilon'_j\gamma'_e k)^2}{2(1+4\epsilon'_j\gamma'_e k)}(1-k)\right], \quad (5)$$

with $k = \frac{\epsilon'_c}{4\epsilon'_j\gamma'_e(\gamma'_e-\epsilon'_c)}$ and r_e is the classical electron radius. Here, $n'_j(\epsilon'_j)$ is the average number density of the seed photons of energy ϵ'_j (in $m_e c^2$) in the blob of the AGN jet which can be directly related to the observed photon flux f_{ϵ_j} (in erg cm^{-2} s^{-1}) from the blazar through [31]

$$\epsilon'_j n'_j(\epsilon'_j) = \frac{2d_L^2}{cR_b'^2\delta^2\Gamma_j^2}\frac{f_{\epsilon_j}}{m_e c^2 \epsilon'_j}, \quad (6)$$

where $\epsilon_j = \delta\epsilon'_j/(1+z)$ [32] relates the photon energies in the observer and comoving jet frame of redshift parameter z, respectively, and d_L is the luminosity distance of the AGN from Earth.

In the proton blazar model, the cosmic ray protons are also supposed to accelerate to very high energies $E'_p = m_p c^2 \gamma'_p$ in the same region of the blazar jet, and the production spectrum shall follow a power law [33,34]

$$N'_p(\gamma'_p) = K_p \gamma_p'^{-\alpha_p}, \quad (7)$$

where α_p is the spectral index, γ'_p is the Lorentz factor of accelerated protons, K_p denotes the proportionality constant which can be found from the same expression as Eq. (2) but for protons, and L'_p is the corresponding jet power in relativistic protons. The number density of relativistic protons is $n'_p = \int N'_p(\gamma'_p) d\gamma'_p$, and the corresponding energy density is $u'_p = 3p'_p = \int m_p c^2 \gamma'_p N'_p(\gamma'_p) d\gamma'_p$, where p'_p is the radiation pressure due to relativistic protons.

We estimate the mechanical luminosity or total kinematic jet power of an AGN jet containing jet frame energy density u' (sum of u'_e, u'_p, and u'_B), pressure p' (sum of p'_e,

p'_p, and p'_B), and matter density ρ' (including cold protons and electrons) from the following relation [19]

$$L_{\rm jet} = \Gamma_j^2 \beta_j c \pi R_b'^2 [\rho' c^2 (\Gamma_j - 1)/\Gamma_j + u' + p'], \quad (8)$$

where we assume the Lorentz factor to be $\Gamma_j \approx \delta/2$, which is quite reasonable, particularly for jets closely aligned to the line of sight of the observer. Applying charge conservation and considering that the number of relativistic electrons will be greater than the number of relativistic protons, the number of cold (nonrelativistic) protons will be equal to the total number of electrons (n'_e) minus the number of hot protons (n'_p). Thus, the cold matter density in protons and in electrons in the blob will be $\rho'_p = (n'_e - n'_p) m_p$, where m_p is the rest mass of a proton and $\rho'_e = n'_{e,c} m_e$, respectively.

When the shock-accelerated cosmic rays interact with the cold matter (protons) of density $n_H = \rho'_p / m_p$ in the blob of the AGN jet, the emissivity of the produced secondary particles of energy $E'_i = m_e c^2 \epsilon'_i$ in the comoving AGN jet frame is given by [8,35–37]

$$Q'_{i,pp}(\epsilon'_i) = \frac{c n_H m_e}{m_p} \int_{\frac{m_e \epsilon'_i}{m_p}} \sigma_{pp}(E'_p) N'_p(\gamma'_p) F_i\left(\frac{E'_i}{E'_p}, E'_p\right) \frac{d\gamma'_p}{\gamma'_p}, \quad (9)$$

where i could be π^0 mesons, electrons (positrons) $e^\pm$, or neutrinos ν, and F_i is the spectrum of the corresponding secondary particles in a single pp collision as given in Kelner *et al.* [37].

Because of the decay of π^0 mesons, the resulting gamma-ray emissivity as a function of gamma-ray energy $E'_\gamma (= m_e c^2 \epsilon'_\gamma)$ is given by [38]

$$Q'_{\gamma,pp}(\epsilon'_\gamma) = 2 \int_{\epsilon'_{\pi,\min}(\epsilon'_\gamma)}^{\epsilon'_{\pi,\max}} \frac{Q'_{\pi,pp}(\epsilon'_\pi)}{[\epsilon'^2_\pi - (\frac{m_\pi}{m_e})^2]^{1/2}} d\epsilon'_\pi, \quad (10)$$

where $\epsilon'_{\pi,\min}(\epsilon'_\gamma) = \epsilon'_\gamma + (\frac{m_\pi}{m_e})^2/(4\epsilon'_\gamma)$ is the minimum energy of a pion required to produce a gamma-ray photon of energy ϵ'_γ (in $m_e c^2$).

When propagating through an isotropic source of low-frequency radiation, the TeV-PeV gamma rays can be absorbed at photon-photon ($\gamma\gamma$) interactions [39]. Thus, the emissivity of escaped gamma rays after $\gamma\gamma$ interaction can be written as [24]

$$Q'_{\gamma,\rm esc}(\epsilon'_\gamma) = Q'_\gamma(\epsilon'_\gamma).\left(\frac{1 - e^{-\tau_{\gamma\gamma}}}{\tau_{\gamma\gamma}}\right). \quad (11)$$

Here, $\tau_{\gamma\gamma}(\epsilon'_\gamma)$ is the optical depth for the interaction and is given by [39]

$$\tau_{\gamma\gamma}(\epsilon'_\gamma) = R'_b \int \sigma_{\gamma\gamma}(\epsilon'_\gamma, \epsilon'_j) n'_j(\epsilon'_j) d\epsilon'_j, \quad (12)$$

where $\sigma_{\gamma\gamma}$ is the total cross section as given in Aharonian *et al.* [39], and $n'_j(\epsilon'_j)$ describes the spectral distributions of target photons. $n'_j(\epsilon'_j)$ is generally assumed to be the observed synchrotron radiation photons produced by the relativistic electron population in the comoving jet frame as given in Eq. (6) because of the low luminosity of accretion disks in BL Lacs [20].

The number of injected electrons (positrons) per unit volume and time in the AGN blob with a Lorentz factor γ'_e coming from $\gamma\gamma$ pair production of high-energy photons as given by Aharonian *et al.* [40] reads

$$Q'_{e,\gamma\gamma}(\gamma'_e) = \frac{3\sigma_T c}{32} \int_{\gamma'_e}^{\infty} d\epsilon'_\gamma \frac{n'_\gamma(\epsilon'_\gamma)}{\epsilon'^3_\gamma} \int_{\frac{\epsilon'_\gamma}{4\gamma'_e(\epsilon'_\gamma - \gamma'_e)}}^{\infty} d\epsilon'_j \frac{n'_j(\epsilon'_j)}{\epsilon'^2_j} \times \left[\frac{4\epsilon'^2_\gamma}{\gamma'_e(\epsilon'_\gamma - \gamma'_e)} \ln\left(\frac{4\gamma'_e \epsilon'_j(\epsilon'_\gamma - \gamma'_e)}{\epsilon'_\gamma}\right) - 8\epsilon'_\gamma \epsilon'_j + \frac{2\epsilon'^2_\gamma(\epsilon'_\gamma \epsilon'_j - 1)}{\gamma'_e(\epsilon'_\gamma - \gamma'_e)} - \left(1 - \frac{1}{\epsilon'_\gamma \epsilon'_j}\right)\left(\frac{\epsilon'^2_\gamma}{\gamma'_e(\epsilon'_\gamma - \gamma'_e)}\right)^2\right], \quad (13)$$

where $n'_\gamma(\epsilon'_\gamma) = (R'_b/c) Q'_{\gamma,pp}$ is the number density of photons of high-energy ϵ'_γ.

The high-energy injected electrons/positrons (Q'_e) including both those ($Q'_{e,\gamma\gamma}$) produced in $\gamma\gamma$ pair production and those ($Q'_{e,\pi}$) created directly due to the decay of $\pi^\pm$ mesons produced in pp interaction [using Eq. (9)] will initiate EM cascades in the AGN blob via the synchrotron radiation, the IC scattering.

In order to determine the stationary state of the population of produced electron distribution $N'_e(\gamma'_e)$, the injection function $Q'_e(\gamma'_e)$ has been used as a source term in the continuity equation for electrons as given by [34]

$$\frac{\partial}{\partial t}[N'_e(\gamma'_e)] = \frac{\partial}{\partial \gamma'_e}\left[\gamma'_e \frac{N'_e(\gamma'_e)}{\tau_c(\gamma'_e)}\right] + Q'_e(\gamma'_e) - \frac{N'_e(\gamma'_e)}{\tau_{ad}}, \quad (14)$$

where we consider the adiabatic timescale as $\tau_{ad} = 2R'_b/c$. The radiative cooling time, considering both inverse-Compton losses and synchrotron losses, is given by [34]

$$\tau_c(\gamma'_e) = \frac{3 m_e c}{4(u'_B + u'_{ph})\sigma_T} \frac{1}{\gamma'_e}, \quad (15)$$

where u'_{ph} is the energy density of photons in the comoving jet frame in equilibrium.

Using the integral expression given by Inoue and Takahara [29], the solution of Eq. (14), i.e., the cascade electron distribution in the stationary state, can be evaluated as

$$N'_e(\gamma'_e) = e^{-\gamma^*_e/\gamma'_e} \frac{\gamma^*_e \tau_{ad}}{{\gamma'_e}^2} \int_{\gamma'_e}^{\infty} d\zeta Q'_e(\zeta) e^{+\gamma^*_e/\zeta}, \quad (16)$$

where

$$\gamma^*_e = \frac{3 m_e c^2}{8(u'_B + u'_{ph})\sigma_T R'_b} \quad (17)$$

indicating the Lorentz factor of the electron when $\tau_c(\gamma'_e) = \tau_{ad}$. Once the equilibrium pair distribution $N'_e(\gamma'_e)$ is known, the associated stationary synchrotron emission is evaluated using Eq. (3), and hence, the observable photon spectrum is found using Eq. (11).

Let $Q'_{\gamma,\mathrm{esc}}(\epsilon'_\gamma)$ be the total gamma ray emissivity from the blob of AGN jet due to all the processes stated above i.e, the synchrotron and the IC radiation of relativistic electrons, the gamma rays produced in pp interaction and the synchrotron photons of EM cascade electrons. The observable differential flux of gamma rays reaching Earth, therefore, can be written as

$$E^2_\gamma \frac{d\Phi_\gamma}{dE_\gamma} = \frac{V'\delta^2\Gamma^2_j}{4\pi d^2_L} \frac{E'^2_\gamma}{m_e c^2} Q'_{\gamma,\mathrm{esc}}(\epsilon'_\gamma) . e^{-\tau^{\mathrm{EBL}}_{\gamma\gamma}}, \quad (18)$$

where $E_\gamma = \delta E'_\gamma/(1+z)$ [32] relates to the photon energies in the observer and the comoving jet frame of redshift parameter z, respectively, with $E'_\gamma = m_e c^2 \epsilon'_\gamma$, and $V' = \frac{4}{3}\pi R'^3_b$ is the volume of the emission region. Here we employ the Franceschini-Rodighiero-Vaccari model [41,42] to find the optical depth $\tau^{\mathrm{EBL}}_{\gamma\gamma}(\epsilon'_\gamma, z)$ for gamma-ray photons due to the absorption by the extragalactic background (EBL) light.

The corresponding flux of muon neutrinos reaching Earth can be written as

$$E^2_\nu \frac{d\Phi_{\nu_\mu}}{dE_\nu} = \xi . \frac{V'\delta^2\Gamma^2_j}{4\pi d^2_L} \frac{E'^2_\nu}{m_e c^2} Q'_{\nu,pp}(\epsilon'_\nu), \quad (19)$$

where $E_\nu = \delta E'_\nu/(1+z)$ [32] relates to the neutrino energies in the observer and the comoving jet frame, respectively, and the fraction $\xi = 1/3$ is considered due to neutrino oscillation.

III. NUMERICAL RESULTS AND DISCUSSION

In the third catalog of AGNs detected by Fermi-LAT listing 1773 objects [43], TXS 0506 + 056 is one of the most luminous objects with an average flux of $6.5(\pm 0.2) \times 10^{-9}$ photons $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ between 1 and 100 GeV. The high-energy neutrino-induced muon track IceCube-170922A detected on September 22, 2017 was found to be positionally coincident with the flaring γ-ray blazar TXS 0506 + 056 [1]. The coincidence detection probability by chance was found to be disfavored at a 3σ confidence level mainly due to the precise determination of the direction of the neutrino [1], although no additional excess of neutrinos was found from the direction of TXS 0506 + 056 near the time of the alert. Assuming a spectral index of 2.13 (2.0) for the diffuse astrophysical muon-neutrino spectrum [44], the most probable energy of the neutrino event was found to be 290 TeV (311 TeV) with the 90% C.L. lower and upper limits being 183 TeV (200 TeV) and 4.3 PeV (7.5 PeV), respectively [1,3]. Extensive follow-up observations by the Fermi-Large Area Telescope [4] in GeV gamma rays and by the MAGIC [45] Telescopes in VHE gamma rays above 100 GeV revealed TXS 0506 + 056 to be active in all EM bands. The redshift of the blazar has been recently measured to be $z = 0.3365$ [46], and the luminosity distance estimated with a consensus cosmology is $d_L \sim 1750$ Mpc [5].

The gamma-ray variability timescale is found as $t_{\mathrm{ver}} \leq 10^5$ s by analyzing the x-ray and gamma-ray light curves [5]. Consequently, to describe the electromagnetic SED of TXS 0506 + 056 over the optical to gamma-ray energy range, we have chosen the size of the emission region of $R'_b = 2.2 \times 10^{16}$ cm with Doppler boosting factor $\delta = 20$ and bulk Lorentz factor of the AGN jet $\Gamma_j = 10.4$, which are strongly consistent with the size inferred from the variability, namely, $R'_b \lesssim \delta c t_{\mathrm{ver}}/(1+z) \simeq 4.5 \times 10^{16}(\delta/20)(t_{\mathrm{ver}}/10^5\ \mathrm{s})$ cm [5].

The low-energy part of the experimental EM SED data can be explained well by the synchrotron emission of the primary relativistic electron's distribution obeying a broken power law as given by Eq. (1) with spectral indices $\alpha_1 = 1.71$ and $\alpha_2 = 4.3$, respectively, before and after the spectral break Lorentz factor $\gamma'_b = 8.5 \times 10^3$. The required kinematic power of relativistic electrons in the blazar jet as given by Eq. (2) and the magnetic field to fit the observed data are $L'_e = 2.3 \times 10^{42}$ erg/s and $B' = 0.38$ G, respectively. Here we have not included the self-absorption of the synchrotron photon's spectrum. When the self-absorption mechanism [23] is included, the resultant spectrum will show a slight mismatch with the observed photon flux at radio energies, particularly, Karl G. Jansky Very Large Array (VLA) and Owens Valley Radio Observatory (OVRO) data.

The inverse-Compton scattering of primary electrons with the target synchrotron photons (also including high-energy photons) comoving with the AGN jet as given by Eq. (4) are also found to produce the lower part of a high-energy bump of EM spectrum, particularly from the NuSTAR experimental data up to the Fermi-LAT data. The number of hot electrons in the blob of the AGN jet are estimated to be $n'_{e,h} = 1.7 \times 10^3$ particles/cm^3, which is required to produce the EM SED due to both synchrotron and inverse-Compton emission. But the acceleration efficiency of electrons in the AGN jet may be quite low, and it can be assumed to be $\chi_e \approx 10^{-3}$ [25–27] due to strong synchrotron and inverse-Compton cooling at relativistic energies, and the total number of electrons including cold electrons is found out to be $n_e = 1.7 \times 10^6$ particles/cm^3.

In the original proton blazar model, high-energy gamma rays are produced through synchrotron radiation by high-energy protons in a strong magnetic field environment. However, due to the low magnetic field strength of the source (obtained from the fitting of the low-energy hump of the SED), the gamma-ray spectrum of the source cannot be modeled with the proton synchrotron radiation. The proton-photon interaction is also found inefficient in the present case due to the low amplitude of the target synchrotron photon field. Instead, the required gamma rays are found to produce interactions of relativistic protons with the ambient cold protons in the blob. The observed higher-energy part of the observed EM SED data, particularly those measured with Fermi-LAT and at the MAGIC Observatory, can be reproduced well by the model as estimated following the best-fit Eq. (18). The spectral index of the energy spectrum of the AGN accelerated cosmic rays is taken as $\alpha_p = -2.13$, which is consistent with the best-fit spectral slope of the observed astrophysical neutrinos of between 194 TeV and 7.8 PeV by the IceCube Observatory [47,48]. The required accelerated primary proton injection luminosity is found to be $L'_p = 10^{46}$ erg/s. The cold proton number density in the jet turns out to be 1.68×10^6 particles/cm^3 under the charge neutrality condition, which provides sufficient targets for hadronuclear interactions with accelerated relativistic protons. The estimated differential gamma-ray spectrum reaching Earth from this AGN is shown in Fig. 1 along with the different space- and ground-based observations. It is clear from the figure that the observed spectrum is correctly reproduced by the model. The detection sensitivity of upcoming gamma-ray experiments like the Cherenkov telescope array (CTA) [49] and the Large High Altitude Air Shower Observatory (LHAASO) [50] are also shown in the figure, which suggests that these experiments will be able to detect gamma rays up to nearly 100 TeV for any similar kind of event if detected in the future and thereby will be able to provide a better understanding of the emission processes.

High-energy neutrinos are produced together with gamma rays in pp interactions. The high-energy neutrino flux on Earth from the blazar TXS 0506 + 056 in the active state has also been estimated following Eq. (19) and shown in Fig. 1 along with the concerned IceCube result. For the estimation of the neutrino flux, no additional adjustable parameters were available; the same parameters used to describe the gamma-ray spectrum lead to the neutrino flux. The total mechanical jet power of the blazar in the jet frame is found to be $L'_{\rm jet} = 1.2 \times 10^{47}$ erg/s, and the physical jet power after the Lorentz boost is $L_{\rm jet} = 1.3 \times 10^{49}$ erg/s. It is noticed that $\eta'_p = L'_p/L_{\rm jet} = 8.5\%$ under the assumption of an electron injection efficiency of about $\chi_e \approx 10^{-3}$; i.e., cosmic ray protons carry 8.5% of the energy of the total jet power in the comoving jet frame, which is generally the expected acceleration efficiency of cosmic rays in astrophysical sources [9,38]. The total jet power in the form of

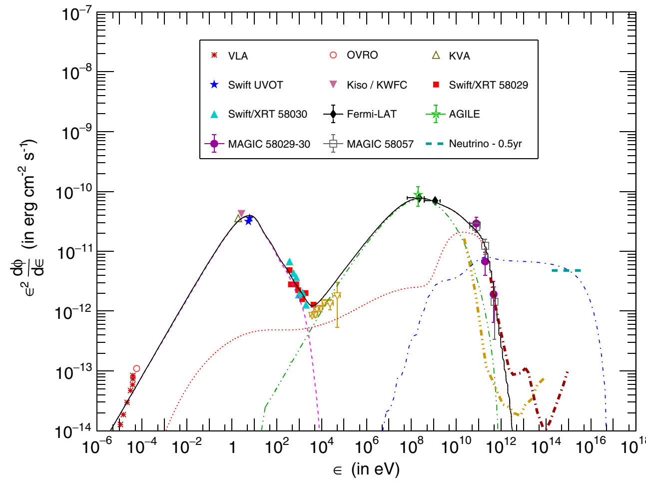

FIG. 1. Estimated differential energy spectrum of gamma rays and neutrinos reaching Earth from the blazar TXS 0506 + 056. The pink small dashed line indicates the low-energy component of the EM spectrum due to synchrotron emission of relativistic electrons. The green long-dash–double-dotted line denotes the gamma-ray flux produced due to inverse-Compton emission of relativistic electrons in seed photon distribution in the comoving jet frame. The red dotted line represents the gamma-ray flux produced from neutral pion decay in a pp interaction together with the cascade emission of electron/positron produced in (pionic) $\gamma\gamma$ absorption. The black continuous line represents the estimated overall differential multiwavelength EM SED. The blue small-dash–single-dotted line indicates the differential muon-neutrino flux reaching Earth. The yellow dash-triple-dotted line and brown long-dash–single-dotted line denote the detection sensitivity of the CTA detector for 1000 h and the LHAASO detector for 1 yr, respectively. The cyan long dashed line indicates the expected level [6] and energy range of the neutrino flux reaching Earth to produce one muon neutrino in IceCube in 0.5 yr, as observed.

magnetic field and relativistic electron and proton kinetic energy calculated as [3] $L^k_{\rm jet} = \Gamma_j^2 \beta_j c \pi R_b'^2 [u'_e + u'_p + u'_B]$ is found to be 10^{48} erg/s. The estimated kinetic jet power of the blazar is consistent with the Eddington luminosity of $L_{\rm edd} \gtrsim 1.3 \times 10^{48}$ erg/s if we assume a supermassive black hole of mass $M_{\rm bh} \gtrsim 10^{10}\ M_\odot$ like blazar S5 0014 + 813 [51]. However, the jet power may exceed the Eddington luminosity during outbursts or for a collimated outflow in a jet because in such situations the jet does not interfere with the accretion flow. Note that a moderate excess of jet power over the Eddington luminosity (within a factor of 10) seems physically viable [6,52].

The MAGIC Collaboration reported that prominent spectral steepening was observed in gamma-ray spectra from the said blazar above ~100 GeV, which confirms the internal $\gamma\gamma$ absorption that is robustly expected as a consequence of pp production of an ~290 TeV neutrino and also restricts the δ to a low value. The cascade emission of electron/positron pairs induced by protons has been estimated following Eqs. (14)–(16) where we include the

TABLE I. Model fitting parameters for TXS 0506 + 056 according to the proton blazar model.

Parameters	Values
δ	20
Γ_j	10.4
θ	1^0
z	0.3365
R'_b (in cm)	2.2×10^{16}
B' (in G)	0.38
u'_B (in erg/cm^3)	5.75×10^{-3}
α_1	-1.71
α_2	-4.3
γ'_b	8.5×10^3
$\gamma'_{e,\mathrm{min}}$	1
$\gamma'_{e,\mathrm{max}}$	1.5×10^5
u'_e (in erg/cm^3)	4.5×10^{-2}
L'_e (in erg/s)	2.3×10^{42}
n_H (in cm^{-3})	1.68×10^6
α_p	-2.13
$E'_{p,\mathrm{max}}$ (in eV)	10^{16}
L'_p (in erg/s)	10^{46}
L^k_{jet} (in erg/s)	10^{48}
N_{ν_μ}	1.007

contribution of high-energy photons along with synchrotron photons in the jet frame as the target for internal $\gamma\gamma$ absorption of the first produced gamma rays in pp interaction. This mechanism is also found to contribute significantly in the hard x-ray to very high energy (VHE) gamma-ray bands. A primary cosmic ray proton spectrum up to $E'_{p,\mathrm{max}} = 10$ PeV in the jet frame and magnetic fields of $B' = 0.38$ G, which is mutually consistent with the synchrotron radiation of electrons for the lower bump in the EM SED, can somewhat describe the observed gamma-ray spectra.

The number of expected muon-neutrino events in time τ can be found from the relation $N_{\nu_\mu} = \tau \int_{\epsilon_{\nu,\mathrm{min}}}^{\epsilon_{\nu,\mathrm{max}}} A_{\mathrm{eff}}(\epsilon_\nu) \cdot \frac{d\phi_{\nu_\mu}}{d\epsilon_\nu} d\epsilon_\nu$, where A_{eff} is the IceCube detector effective area at the declination of the TXS 0506 + 056 in the sky [2,53,54]. We found that the expected muon-neutrino events in the IceCube detector from the blazar in the 200 TeV and 7.5 PeV energy range are about $N_{\nu_\mu} = 1.007$ events in 0.5 years for the flaring VHE emission state with $E'_{p,\mathrm{max}} = 10$ PeV. The expected muon-neutrino events are about $N_{\nu_\mu} = 2.6$ for the same scenario but in the energy range of 32 TeV and 3.6 PeV with $E'_{p,\mathrm{max}} = 10$ PeV, which is in good agreement with the effective energy range [2] of IceCube for astrophysical neutrinos. The model fitting parameters to match the EM SED as well as muon-neutrino event are summarized in Table I.

The VHE gamma-ray flux from the blazar is found to be variable, i.e., increasing by a factor of up to ~6 within one day from the low state (quiescent state) to the flaring state. The flux variability found mainly in the high-energy component but not in the lower bump of EM spectra from the source disfavors the inverse-Compton origin for such variabilities. There may be two possible scenarios for such variabilities: (i) The VHE gamma-ray flux in the low state is leptonic in origin, i.e., via inverse-Compton emission from electrons up-scattering synchrotron photons (synchrotron-self-Compton scenario [55–57]) or photons from the ambient fields (external inverse-Compton [58,59]), but consequently no neutrinos will produce. The higher flux of gamma rays in the flaring state can be interpreted when the blazar jet meets the external cloud [13,21,60], which will provide sufficient target matter (protons) for interaction with accelerated cosmic rays to produce the observed high-energy gamma rays and neutrinos efficiently. (ii) The VHE gamma-ray flux in both the low state and flaring state can be explained in a hadronic interaction model using a proton blazar model. In this scenario, the observed gamma-ray flux can be explained well with the hadronic pp interaction of accelerated cosmic rays of comparatively harder spectral slope (~2.28) and lowering the maximum energy of accelerated cosmic rays with an ambient cold proton (in the charge neutrality condition with coaccelerated electrons) in the low state of the blazar compared to the flaring state and subsequently produce neutrinos (of event $N_{\nu_\mu} = 0.13$ in 0.5 yr) as well.

IV. CONCLUSION

The coincident detection of the neutrino event IceCube-170922A with the gamma-ray flaring blazar TXS 0506 + 056 provides support for the acceleration of cosmic rays in the blazar jet in the diffusive shock-acceleration process [1]. In the framework of the proton blazar model, our findings suggest that relative contributions to the total jet power of cold protons, accelerated protons, magnetic field, and accelerated electrons obtained on the basis of charge neutrality can explain both the low- and high-energy bump of the multiwavelength EM SED and also the observed neutrino event IceCube-170922A from the flaring blazar TXS 0506 + 056 consistently. We find that the maximum energy of the cosmic ray particle achievable in the blazar is 1 order less than the ankle energy of the cosmic ray energy spectrum or 2×10^{17} eV in the observer frame and is required to explain consistently the observed gamma-ray and neutrino signal from the source. The upcoming gamma-ray experiments like CTA [49] and LHAASO [50], which are very sensitive up to 100 TeV energies, may provide a clearer picture of the physical origin of gamma rays if more events like TXS 0506 + 056 are detected in the future.

The gamma-ray flux in the quiescent state of the source TXS 0506 + 056 is smaller by an order or so. Such a fact disfavors the cloud-jet interaction model, as in the absence of the cloud, the gamma-ray flux should decrease substantially. One may argue that the quiescent state gamma-ray flux is due to the inverse-Compton process by relativistic electrons. But a fine-tuning is needed to produce the same kind of shape and peak position of the second hump of the EM SED in both the enhanced and quiescent states if two different processes (hadronic and inverse Compton) are invoked to explain the observations. Recently, the IceCube Collaboration reanalyzed their historical data and reported significant evidence for a flare of 13 muon-neutrino events in the direction of TXS 0506 + 056 between September 2014 and March 2015 [1]. Surprisingly, the blazar TXS 0506 + 056 was found to be in the quiescent state of both the radio and GeV emission at the arrival time window of such a neutrino flare [53]. Such an observation favors the hadronic interaction mechanism for the production of observed high-energy gamma rays as well as neutrinos for both the low and flaring states of the blazar. More elaborate studies are required to understand the production mechanism of the muon-neutrino events from TXS 0506 + 056 in the quiescent state.

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