Photohadronic Model for the Neutrino and Gamma-Ray Emission from TXS 0506+056

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Abstract

The detection of a high-energy muon neutrino on 2017 September 22 by the IceCube neutrino detector coincides with the multiwavelength flaring from the BL Lac object TXS 0506+056, most likely confirming an active galactic nucleus as a source of high energy cosmic rays and neutrinos. Using the photohadronic model, we have explained the very high energy γ-rays observed by MAGIC telescopes a few days after the neutrino event and extend the model to calculate the neutrino flux at different windows consistent with the flaring period of TXS 0506+056 and compared with the IceCube and MAGIC estimates. We also use this model to estimate the neutrino flux from the flaring of FSRQ PKS B1424-418, which is believed to be associated with the 2 PeV neutrino event observed by IceCube.

Unified Astronomy Thesaurus concepts: Particle astrophysics (96); BL Lacertae objects (158); Neutrino astronomy (1100); Gamma-ray sources (633); Relativistic jets (1390)

1. Introduction

On 2017 September 22, the IceCube neutrino observatory detected a track-like neutrino event with energy $E_{\nu} \sim 290$ TeV (IceCube-170922A; IceCube Collaboration et al. 2018a). This neutrino event is spatially and temporally associated with TXS 0506+056, a blazar at a redshift of $z = 0.3365 \pm 0.0010$, which was in a flaring state in the γ-ray energy range at that very moment (Padovani et al. 2018). Extensive follow-up observations from radio to TeV energy bands revealed that the blazar TXS 0506+056 was active during this period and enhanced emissions in all these energy bands were observed, notably the GeV emission is found to be at a high state as observed by Fermi-LAT (Keivani et al. 2018). On September 23, ~4 hr after the neutrino alert, H.E.S.S. telescopes (Aharonian et al. 2006) observed for 1.3 hr and similarly, ~12 hr after the IceCube-170922A event, the VERITAS telescopes (Holder et al. 2006) had a 1 hr follow-up observation in the direction of TXS 0506+056. Both the telescopes also made additional observations on subsequent nights without any success. However, the MAGIC telescopes observed very high-energy (VHE) γ-rays above 100 GeV for the first time from TXS 0506+056 on September 28 (Ansoldi et al. 2018). Earlier studies to observe correlation between high energy neutrinos and the blazars suffered from poor angular resolution and absence of simultaneous observation of flares. In 2016, Kadler et al. reported a PeV neutrino event from the blazar PKS B1424-418, which was detected by the IceCube neutrino observatory, but it was a shower event with average median angular error 12° (Kadler et al. 2016).

The direct association between a neutrino event, IceCube-170922A, and a point source, TXS 0506+056 was reported for the first time in multiwavelength observations with high significance (IceCube Collaboration et al. 2018a; Murase et al. 2018). Several models, particularly leptonic and photohadronic have attempted to explain the observed correlation (Ansoldi et al. 2018; Keivani et al. 2018; Sahakyan 2018; Cerruti et al. 2019; Gao et al. 2019; Xue et al. 2019). Most probably, this provides direct evidence that active galactic nuclei (AGNs) can accelerate high energy cosmic rays, and produce neutrinos from the $p\gamma$ and/or $pp$ interactions.

Blazars are a subclass of AGN and the dominant extragalactic population in γ-rays (Acciari et al. 2011), show rapid variability in the entire electromagnetic spectrum, and have nonthermal spectra (Abdo 2010). Their jet orientation is close to the observer’s line of sight (Urry & Padovani 1995) and powered by matter accretion into the supermassive black hole at the center. Based on their optical spectra, blazars are divided into flat spectrum radio quasars (FSRQs) and BL Lac objects (Abdo et al. 2010). The FSRQs are relatively luminous and show strong optical–UV emission lines, whereas, BL Lac objects are less luminous and show only weak emission lines. The spectral energy distribution (SED) of these blazars has a double peak structure in the ν–νF_ν plane (Abdo et al. 2010). The low energy peak corresponds to the synchrotron radiation from a population of relativistic electrons in the jet and the high energy peak believed to be either due to the scattering of the high energy electrons with their self-produced synchrotron photons in the jet (self-synchrotron Compton or SSC; Maraschi et al. 1992; Gao et al. 2013) or from external sources, such as photons from the accretion disk, broad line regions, or the dusty torus (external Compton or EC; Dermer & Schlickeiser 1993; Sikora et al. 1994; Blazejowski et al. 2000). In general, the leptonic models are very successful in explaining the multiwavelength emission from blazars (Fossati et al. 1998; Ghisellini et al. 1998; Tavecchio et al. 2011; Boettcher et al. 2013). Depending on the position of the synchrotron peak, the BL Lac objects are further divided into low synchrotron peaked (LSP), intermediate synchrotron peaked (ISP), and high synchrotron peaked (HSP) blazars, respectively (Abdo et al. 2010). For LSP, the synchrotron peak has frequency $\nu_{\text{peak}} < 10^{14}$ Hz, for ISP it is in the range $10^{14}$ Hz < $\nu_{\text{peak}} < 10^{15}$ Hz and for HSP it satisfies $\nu_{\text{peak}} > 10^{15}$ Hz. Similarly there is also a shift of the SSC peak toward higher energy from LSP to HSP.

In the traditional scenario, FSRQs are believed to be promising sources of high energy neutrinos as they contain...
high density photons in the jet and the $p\gamma$ process can be effective (Dermer et al. 2014). But BL Lac objects have relatively low photon density in the UV to soft X-ray region hence the $p\gamma$ process to produce neutrinos is not efficient (Murase et al. 2018; Righi et al. 2019). If TXS 0506+056 is a BL Lac object, its association with the $\sim 290$ TeV neutrino is nontrivial to interpret. HSP blazars have Compton dominance (CD) $\sim 0.1$ (Padovani et al. 2019); however, TXS 0506-056 has CD $\sim 4.5$, implying that this may not be an HSP but rather an FSRQ with a relatively high synchrotron peak (Sahu et al. 2019a). Recently, Padovani et al. reclassified this as a masquerading BL Lac object, namely an FSRQ with a relatively high synchrotron peak (Padovani et al. 2019).

In this work our motivation is to use the photodiffractive model to explain the VHE $\gamma$-rays and neutrino fluxes from TXS 0506+056 and PKS B1424-418.

2. Photodiffractive Model

Previously, we have shown that the multi-TeV emission from HSP blazars can be explained very well with the photodiffractive model (Sahu et al. 2019b). This model relies on the standard interpretation of the leptonic model to explain both low and high energy peaks by synchrotron and synchrotron self-Compton (SSC) photons, respectively, as in the case of any other AGN and blazars. Thereafter, it is assumed that the flaring occurs within a compact and confined volume of size $R'_{c}$ inside the blob of radius $R_{b}$, with $R'_{c} \ll R_{b}$ (where ‘ implies the jet comoving frame and without ‘ is in the observer frame). During the flaring, the compact internal jet is moving slightly faster than the outer one. However, for simplicity, we take their bulk Lorentz factor $\Gamma_{b} \approx \Gamma_{ext} \approx 10$. Geometrically this represents a double jet structure, one compact and smaller cone, which is enclosed by a bigger one along the same axis; the geometry of this model is discussed in Figure 1 of Sahu et al. (2016). Fermi accelerated protons having a power-law spectrum $dN/dE_{p} \propto E_{p}^{-\alpha}$ (Dermer & Schlickeiser 1993) with the power index $\alpha \geq 2$ interact with the background photons in the inner jet region to produce the $\Delta$-resonance, which subsequently decays to $\gamma$-rays via an intermediate neutral pion and to neutrinos through a charged pion (Sahu et al. 2012). In most of the cases $\alpha = 2$ is considered, and for our calculation we also take this value. The kinematical condition to produce $\Delta$-resonance is $E_{p} \epsilon_{\gamma} = 0.32 \Gamma D (1 + z) \Gamma^{2}$ GeV$^2$, where $E_{p}$ and $\epsilon_{\gamma}$ are the observed proton and seed photon energies respectively; $\Gamma$, $D$, and $z$ are the bulk Lorentz factor, Doppler factor, and redshift, respectively. The observed VHE $\gamma$-ray energy is $E_{\gamma} = 0.1 D \Gamma^{2} E_{p}$.

The flaring region we assume $n'_{e,f}$ is much higher than the rest of the blob $n'_{e}$ (nonflaring) i.e., $n'_{e,f}(\epsilon_{\gamma}) \gg n'_{e}(\epsilon_{\gamma})$. As the inner jet is buried within the outer jet, it cannot be observed directly. However, by assuming that the Eddington luminosity is equally shared by the jet and the counter jet, the photon density in the inner jet can be constrained to be $n'_{f} \ll L_{\text{Edd}}/(8 \pi R^{2}_{f} \epsilon_{\gamma}^{2})$ (Sahu 2019).

The photon density in the outer region can be calculated from the observed flux from the SED and, using the scaling behavior, the $n'_{e,f}$ can be expressed in terms of $n'_{e}$ (Sahu et al. 2016). The outer jet is always there and responsible for the quiescent state of the blur while the inner jet is transient and responsible for the flaring event. In a canonical jet scenario the photodiffractive process is inefficient in explaining the multi-TeV emission due to low photon density. To explain the high energy peak, efficient acceleration of relativistic protons to ultra-high energies in the jet outflow is required and at the same time the jet kinetic power has to exceed the Eddington luminosity by orders of magnitude (Cao & Wang 2014). However, our compact inner jet scenario eliminates this extreme energy requirement.

The interaction of VHE $\gamma$-rays with the extragalactic background light (EBL) produces electron–positron pairs and depletes the VHE $\gamma$-ray flux by a factor of $e^{-\tau_{\gamma}}$, where $\tau_{\gamma}$ is the optical depth for the process $\gamma\gamma \to e^{+}e^{-}$. To account for the attenuation of high energy gamma-rays well known EBL models are used (Dominguez et al. 2011; Franceschini et al. 2008) and the observed VHE flux is expressed as

$$F_{\gamma}(E_{\gamma}) = F_{\gamma, \text{int}}(E_{\gamma}) e^{-\tau_{\gamma}},$$

where the intrinsic flux is

$$F_{\gamma, \text{int}}(E_{\gamma}) = F_{0} \left( \frac{E_{\gamma}}{\text{TeV}} \right)^{-\delta+3},$$

where $\delta = \alpha + \beta$ and $F_{0}$ is the normalization constant determined from the observed VHE SED. During the flaring period, the background seed photon flux behaves as a power law $\Phi \propto E_{\gamma}^{-\beta}$, where $0 < \beta \leq 1.0$ (Sahu et al. 2018a). Recently, the flaring of HSP blazars have been classified into roughly three categories depending on the value of $\delta$ (Sahu et al. 2019a). Low state emission corresponds to $\delta = 3.0$, high state corresponds to $2.6 < \delta < 3.0$, and very high state emission takes place when $2.5 \leq \delta \leq 2.6$. As the value of proton spectral index $\alpha \geq 2$ is known, for different emission states the value of $\beta$ is constrained accordingly.

3. Results

We use the photodiffractive model to explain the VHE $\gamma$-ray SED and estimate the neutrino flux from TXS 0506+056. Using the same approach, we fit the $\gamma$-ray spectrum of PKS B1424-418 and estimate the neutrino flux.
3.1. VHE $\gamma$-Rays from TXS 0506+056

On 2017 September 24, the MAGIC telescopes observed TXS 0506+056 under nonoptimal atmospheric conditions and no $\gamma$-rays were detected. Following the alert of enhanced $\gamma$-ray emission by Fermi-LAT, again MAGIC observed for 13 hr starting on 2017 September 28 and detected VHE $\gamma$-rays in the energy range $75 \text{ GeV} \leq E_{\gamma} \leq 366 \text{ GeV}$ when it was in a flaring state (Ansoldi et al. 2018). Taking the jet bulk Lorentz factor $\Gamma = 22$, the viewing angle $\theta_{\text{view}} = 0.8^\circ$, and the Doppler factor $D \approx 40$, MAGIC Collaboration explained the emission using inverse Compton upscattering of external photons by accelerated electrons and the photohadronic interaction. Here we use the photohadronic model to explain the observed VHE $\gamma$-rays.

In the photohadronic scenario, the VHE SED can be explained very well by taking $\delta = 2.9$, $F_0 = 6.0 \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$ (high state), and $3.0$, $F_0 = 5.0 \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$ (low state) with the EBL correction (Franceschini et al. 2008), as shown in Figure 1. Using $\Gamma$ and $D$ of MAGIC, the observed VHE spectrum in the energy range $75 \text{ GeV} \leq E_{\gamma} \leq 366 \text{ GeV}$ is produced from the interaction of Fermi-acceleration protons in the energy range $50 \text{ MeV} \leq E_p \leq 3.7 \text{ TeV}$ with the seed photons in energy range $43 \text{ MeV} \leq \epsilon_{\gamma} \leq 211 \text{ MeV}$, which is in the SSC region. In the jet comoving frame the $\gamma$-ray energy $E_{\gamma}^c$ and the seed photon energy $\epsilon_{\gamma}^c$, are, respectively, in the ranges $2.3 \text{ GeV} \leq E_{\gamma}^c \leq 12.2 \text{ GeV}$ and $1.4 \text{ MeV} \leq \epsilon_{\gamma}^c \leq 7.1 \text{ MeV}$. Here we use $R_p' \approx 10^{13} \text{ cm}$ and $R_{\gamma}^b \approx 10^{16} - 10^{17} \text{ cm}$ (Ansoldi et al. 2018; Keivani et al. 2018).

The 12.2 GeV photon produced in the inner region can in principle interact with the seed photons and depletes its energy by producing $e^+e^-$ pairs. However, the mean free path $\lambda_{\gamma\gamma}$ for 12.2 GeV photon interacting with $\epsilon_{\gamma} \approx 1.4 \text{ MeV}$ seed photon is $\lambda_{\gamma\gamma} > R_p'$ if the photon density is $n_{\gamma,f} \lesssim 10^{10} \text{ cm}^{-3}$. This density is also consistent with the moderate efficiency of $\Delta$-resonance process (Sahu et al. 2018b), hence, attenuation in $\gamma$-rays in the inner jet due to $e^+e^-$ production is negligible. It is worth mentioning here that, to fit the observed VHE spectrum of TXS 0506+056, it is not necessary to know the detail of the seed photon density, only the value of $\delta$ is enough to fit it. But to know the range of $\epsilon_{\gamma}$, it is necessary to know the value of $D$ and $\Gamma$. Due to the adiabatic expansion of the inner jet, the seed photons with density $n_{\gamma,f} \lesssim 10^{10} \text{ cm}^{-3}$ will decrease after crossing into the outer region.

3.2. IceCube-170922A Neutrino Event

The MAGIC telescopes observed VHE $\gamma$-rays after $\sim 6$ days of the 290 TeV neutrino event (Ansoldi et al. 2018; IceCube Collaboration et al. 2018a). It is possible that during the neutrino emission period, the flaring was in a very high state and in the next 6 days it slowly decayed to a high or a low state. A similar behavior was observed from 2009 May 1 flaring of Markarian 501 (Mrk 501) when the flux increased by a factor of four in just $0.5$ h (very high state) and afterwards it decreased but remained in an elevated state for the next $2-3$ days (high state; Ahnen et al. 2017). Had it not been observed during the very high state period, it would have been assumed that Mrk 501 was in a high state throughout the above observation period. Keeping this in mind, we assume a similar behavior for the flaring of TXS 0506+056. Most probably, on 2017 September 22 the flare was in a very high emission state with $\delta = 2.5-2.6$, when the intrinsic flux might have increased by an order of magnitude in a very short time interval during which the 290 TeV neutrino emission took place through the photohadronic process. The $\gamma$-ray energy and its flux subsequently decreased to a high/low state in the next few days, and the increase in the intrinsic flux was mild (high state)/constant (low state) as can be seen from Figure 1.

For $p\gamma \rightarrow \Delta^+$ to take place within the inner compact jet region, the timescales should satisfy

$$t_{\text{acc}}^< < t_{\text{acc}}^< < t_{\gamma p},$$

(3)

where $t_{\text{syn}} \approx R_p' \approx 3.34 \times 10^4 R_{\gamma,p,15} \text{s}$ is the dynamical timescale, $t_{\text{acc}} = 10\eta E_p'/e B'$ is the acceleration timescale, and $t_{\gamma p} = (\sigma_pK_p n_{\gamma,f})^{-1}$ is the $\gamma p$ interaction timescale, where $K_p = 0.2$. The parameter $\eta$ characterizes the properties of magnetic disturbances responsible for the acceleration and can vary between $10$ and $100$ (Cerruti et al. 2015). All other timescales, e.g., $t_{\text{HIH}}$ (Bethe–Heitler; BH) and $t_{\text{syn}}$ (synchrotron) should be larger than $t_{\gamma p}$.

In the present scenario, the Larmor radius of the high energy proton must not exceed the inner jet size $R_p' \sim 10^{15} \text{ cm}$ and this corresponds to maximum proton energy $E_{p,\text{max}}' \approx 300 \text{ PeV}$ for a magnetic field $B' \sim 1 \text{ G}$. The $E_{p} = 290 \text{ TeV}$ corresponds to the observed proton energy $E_p = 20E_{p,\text{max}}' = 5.8 \text{ PeV}$ and in the comoving frame it will be $E_{p}' = 352 \text{ TeV}$. Correspondingly, the seed photon energy to produce $\Delta$-resonance will be $\epsilon_{\gamma} = 0.91 \text{ keV}$ in the comoving frame and in the observer frame $\epsilon_{\gamma} = 27.18 \text{ keV}$. The seed photons with $\epsilon_{\gamma} = 0.91 \text{ keV}$ and assuming $n_{\gamma,f} \approx 10^{10} \text{ cm}^{-3}$ in the inner jet region will expand adiabatically to the outer region of radius $R_p'$ thus decreasing the number density to $n_{\gamma} \approx 10^{4} \text{ cm}^{-3}$. The observed flux corresponding to these X-ray photons is estimated to be $F_{\text{keV}} \approx 1.4 \times 10^{-12} \text{ erg cm}^{-2} \text{s}^{-1}$ and is below the observed limit.

The acceleration time for the proton in the jet is

$$t_{\text{acc}}^> = 3.9 \times 10^4 \left(\eta \over 100\right) \left(E_{p}' \over 352 \text{ TeV}\right) \left(B' \over 1 \text{ G}\right)^{-1} \text{ s}.$$  

(4)

The optical depth for the $p\gamma \rightarrow \Delta^+$ process within the inner jet region is given by

$$\tau_{\gamma p} = n_{\gamma,f} R_p' \sigma_{\gamma p},$$

(5)

and we consider $\tau_{\gamma p} \ll 1$, so that excess production of VHE $\gamma$-rays and neutrinos can be avoided. This corresponds to $n_{\gamma,f} \ll 2 \times 10^{12} \text{ cm}^{-3}$. By assuming that the same neutrino is produced in the outer jet region, the photon density is estimated to be $n_{\gamma,f} \approx 1.5 \times 10^{12} \text{ cm}^{-3}$. So, the photon density in the jet is constraint to be

$$1.5 \times 10^{4} \text{ cm}^{-3} \ll n_{\gamma,f} \ll 2 \times 10^{12} \text{ cm}^{-3}.$$  

(6)

Here we consider $2 \times 10^{6} \text{ cm}^{-3} \lesssim n_{\gamma,f} \lesssim 2 \times 10^{11} \text{ cm}^{-3}$, which corresponds to an optical depth in the range $10^{-4} \lesssim \tau_{\gamma p} \lesssim 10^{-1}$. By taking $n_{\gamma,f} \approx 2 \times 10^{11} \text{ cm}^{-3}$, we obtain $t_{\gamma p} \approx 1.7 \times 10^9 \text{s}$ and for lower density $t_{\gamma p}$ will be higher, thus the condition given in Equation (3) is satisfied. We also estimated the timescale for the BH process in the inner jet and found that $t_{\gamma p}^> > t_{\gamma p}^<$. The Astrophysical Journal, 898:103 (7pp), 2020 August 1

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Table 1
The Neutrino Normalization Constant $A_{\nu}$, Neutrino Flux at $E_{\nu} = 290$ TeV, $E_{\nu}(290$ TeV) and the Integrated Neutrino Flux $F_{\nu}^{\text{int}}$ Are Shown for $\delta = 2.5$ and 2.6 at Different Time Windows

| $T$ (days) | $\delta$ | $A_{\nu}$ | $E_{\nu}(290$ TeV) | $F_{\nu}^{\text{int}}$ |
|-----------|---------|-----------|---------------------|-------------------|
| 19        | 2.5     | $3.06 \times 10^{-16}$ | $1.34 \times 10^{-11}$ | $1.23 \times 10^{-10}$ |
|           | 2.6     | $3.60 \times 10^{-16}$ | $1.41 \times 10^{-11}$ | $1.12 \times 10^{-10}$ |
| 60        | 2.5     | $1.14 \times 10^{-16}$ | $4.23 \times 10^{-12}$ | $3.90 \times 10^{-11}$ |
|           | 2.6     | $1.32 \times 10^{-16}$ | $4.48 \times 10^{-12}$ | $3.55 \times 10^{-11}$ |
| 158       | 2.5     | $3.67 \times 10^{-17}$ | $1.61 \times 10^{-12}$ | $1.48 \times 10^{-11}$ |
|           | 2.6     | $4.33 \times 10^{-17}$ | $1.70 \times 10^{-12}$ | $1.35 \times 10^{-11}$ |
| 360       | 2.5     | $1.61 \times 10^{-18}$ | $7.05 \times 10^{-13}$ | $6.49 \times 10^{-12}$ |
|           | 2.6     | $1.90 \times 10^{-17}$ | $7.47 \times 10^{-12}$ | $5.91 \times 10^{-12}$ |

Note. $A_{\nu}$ is expressed in units of erg$^{-1}$cm$^{-2}$ and fluxes are given in units of erg$^{-1}$cm$^{-2}$s$^{-1}$.

As the photohadronic process and the BH pair production process $p\gamma \rightarrow pe^+e^-$ take place in the same photon background, in principle, the BH process can compete with the photopion process (Cerruti et al. 2019). However, compared to the photopion process, the BH process has a lower threshold energy and energy loss by the proton to produce lepton pairs is low as the rest mass of the lower threshold energy and energy loss by the proton to produce lepton pairs is low as the rest mass of the electron $m_e = 135$ MeV. Above the pion production threshold, the photopion process is dominant over the BH process. Here, the proton energy $E_p \approx 352$ TeV, which is much above the pion production threshold in the seed photon background, hence, the main energy loss process from the protons is through the photopion process (Berezinsky & Grigoriev 1988; Geddes et al. 1995).

The nonthermalization of electrons by $e\gamma$ interaction implies $n_{e\gamma} < 1.5 \times 10^9$ cm$^{-3}$. We calculate the VHE luminosity $L_{\text{VHE}} \approx 2.2 \times 10^{45}$ erg s$^{-1}$ and by taking $\tau_{p\gamma} \approx 10^{-2}$, the isotropic proton luminosity is $L_p \approx 1.7 \times 10^{48}$ erg s$^{-1}$. However, $L_p$ can be modified by changing $\tau_{p\gamma}$ and the proton fraction accelerated to VHE energies. In other photohadronic scenarios, the maximum proton luminosity consistent with the SED is estimated as $L_{p,\text{max}} \approx 2 \times 10^{39}$ erg s$^{-1}$ (Keivani et al. 2018).

The 290 TeV neutrino energy corresponds to observed $\gamma$-ray energy $E_\gamma \sim 580$ TeV. These VHE $\gamma$-rays attenuate by interacting with the low energy seed photons ($\epsilon_\gamma \sim 46$ eV) in the inner and outer regions of the jet to produce $e^+e^-$ pairs. Subsequently these lepton pairs will produce electromagnetic cascades of lower energy in the surrounding photon medium and magnetic field. Furthermore, such high energy photons will be severely attenuated by EBL before reaching the detector. However, the neutrino will escape the jet carrying the information about the parent proton and seed photon spectra. Although the cascading process of high energy $e^+e^-$ might have initiated simultaneously along with the IceCube neutrino event, the former was not observed. Also, after $\sim 6$ days of the neutrino event, VHE $\gamma$-rays were observed by MAGIC telescopes. So, even though cascade emission from secondary leptons was important, it will neither affect the neutrino flux nor the VHE spectrum.

We assumed that the VHE neutrinos are produced during the very high flaring emission state when the photon flux has increased dramatically. Then, it is natural to ask why VHE neutrinos were not observed from the flaring of Mrk 501 on 2009 May 1 even though it was in a very high state. Note that the maximum energy of the proton depends on the acceleration timescale and the magnetic field in the jet. For Mrk 501, the flare duration was for about 1.5 hr (MJD 54952.35–54952.41) and $B' \approx 0.25$ G, which gives $E_{p,\text{max}} \sim 12$ TeV (Ahnen et al. 2017). However, to produce $E_{p,\text{max}} \sim 352$ TeV, as in the case of TXS 0506+056, the very high flaring state has to continue for about half a day in the presence of $B' \sim 1$ G. Thus, the inner jet in Mrk 501 probably had a low magnetic field and, additionally, the very high state did not continue longer at a stretch to accelerate the protons to sufficiently high energy even though the active state of the source was much longer.

3.3. Neutrino Flux Estimation

The number of neutrino events $N_\nu$ observed by IceCube at a time period $T$ is given by

$$N_\nu = T \int_{E_{\nu}^1}^{E_{\nu}^2} \frac{dN}{dE_\nu} A_{\text{eff}}(E_\nu) dE_\nu,$$

where $E_{\nu}^1,2 = E_{\gamma,1,2}(1 + z)$ and $A_{\text{eff}}$ is the effective area of neutrino in IceCube (IceCube Collaboration 2018). The neutrino differential flux in photohadronic model is a power law

$$\frac{dN}{dE_\nu} = A_\nu \left( \frac{E_\nu}{E_0} \right)^{-\delta+1},$$

where $A_\nu$ is the normalization constant we take $E_0 = 100$ TeV. We assume that the VHE neutrinos are produced during the VHE flaring state of TXS 0506+056 from the $\pi^+\rightarrow\nu_{\mu}$ decay with $2.5 \leq \delta \leq 2.6$. This gives

$$A_\nu = \left( \frac{N_\nu}{T \int_{E_{\nu}^1}^{E_{\nu}^2} \left( \frac{E_\nu}{E_0} \right)^{-\delta+1} A_{\text{eff}}(E_\nu) dE_\nu} \right).$$

The integral in the denominator can be evaluated numerically for different values of $\delta$. The IceCube observed a single muon neutrino event ($N_\mu = 1$) of $E_{\nu} = 290$ TeV. For $\delta = 2.5, 2.6$ and $A_{\text{eff}}$ for muon neutrino with the integration limits 38 TeV–7 PeV, we obtain

$$A_\nu \approx 1 \times \left\{ \begin{array}{ll} 5.0 \times 10^{-10} \text{erg}^{-1} \text{cm}^{-2}, & \delta = 2.5 \\ 5.9 \times 10^{-10} \text{erg}^{-1} \text{cm}^{-2}, & \delta = 2.6 \end{array} \right\}$$

The multiwavelength observation of TXS 0506+056 suggests that its most prolonged active period was about $\sim 0.5 - 1$ yr (Ansoldi et al. 2018). The shortest time period when the most significant excess of $\gamma$-rays were found is the time window centered at 2017 September 22 with a duration of 19 days (IceCube Collaboration et al. 2018a). As the number of events are proportional to the active phase duration, we consider four time windows for our analysis, namely $T = 19, 60, 158,$ and 360 days consistent with the IC86 runs (IceCube Collaboration et al. 2018a).

The neutrino flux is given by

$$F_\nu(E_\nu) = F_0 \left( \frac{E_\nu}{E_0} \right)^{-\delta+3}.$$
where \( F_{\nu,0} = A_\nu E_\nu^2 \). We calculate the integrated neutrino flux \( F_{\nu,\text{int}} \) for different time windows with \( \delta = 2.5, 2.6 \) as shown in Table 1. The predicted neutrino fluxes for different time windows are within the upper limit reported in IceCube Collaboration et al. (2018b). We compare our results with the flux predicted by MAGIC collaboration at 290 TeV (Ansoldi et al. 2018) and find that for \( T = 158 \) days our values are consistent.

### 3.4. Neutrino Event HESE-35 from PKS B1424-418

The IceCube has so far detected three shower type neutrino events in PeV energies, of which two events are of energy \( \sim 1 \) PeV and the third event (HESE-35) detected on 2012 December 4 at an energy of about 2 PeV (Aartsen et al. 2014). A spatial and temporal association of HESE-35 neutrino event with the flaring FSRQ PKS B1424-418 at a redshift of \( z = 1.522 \) is suggested by analyzing the flaring activity in the latter (Kadler et al. 2016). In the time window between 2012 July 16 and 2013 April 30, a period of \( \sim 9 \) months, the FSRQ had undergone a major outburst and \( \gamma \)-rays in the energy range 100 MeV–300 GeV were observed by Fermi-LAT. Also enhanced emission of X-rays as well as optical and radio emissions were observed by different telescopes (Tavecchio et al. 2013). The arrival time of the 2 PeV neutrino event coincides with the time window in which the FSRQ had undergone a major outburst (Kadler et al. 2016). Using a leptohadronic model, with a subdominant hadronic contribution, the multiwavelength SED is reproduced. It is also shown that the time-wise correlation between the neutrino event and burst phase is weak (Gao et al. 2017).

The SED around the high energy peak (second peak) is due to the SSC scattering which Fermi-LAT observes. During the high-fluence outburst, the spectrum observed by Fermi-LAT has a sudden change in slope above \( \sim 22 \) GeV and the last two points do not fit with the two log parabola approximation (Figure 2). It is possible that the observed flux above 40 GeV might have a different origin than the SSC one, possibly from neutral pion decay from the photodihadronic process. We fit the VHE flux using the photodihadronic model with \( \delta = 2.9 - 3.0 \) and \( F_0 = (5.0 - 3.7) \times 10^{-11} \text{ erg cm}^{-2} \text{s}^{-1} \) in the energy range \( 43 \text{ GeV} \leq E_{\nu} \leq 139 \text{ GeV} \), as shown in Figure 2. These values of \( \delta \) imply that the outburst was either in a high emission or in a low emission state.

For PKS B1428-418, we take \( D = 32, \Gamma = 20 \) used by Tavecchio et al. (2013) and consider \( R_{\nu} \sim 10^{46} \text{ cm}^{-2} \). The nonthermalization condition of electrons by \( e\gamma \) interaction implies \( n_{e,\gamma} < 1.5 \times 10^{10} \text{ cm}^{-3} \). The VHE luminosity \( L_{\nu,0.04-0.15\text{GeV}} \sim 3.1 \times 10^{47} \text{ erg s}^{-1} \), which corresponds to an isotropic proton luminosity of \( L_p \sim 2.3 \times 10^{50} \text{ erg s}^{-1} \) for \( \tau_{\nu,p} \sim 10^{-2} \). Following the same argument as of TXS 0506+056, we get that the timescales are consistent with Equation (3) and are given as \( t_{\text{dyn}} \sim 3.3 \times 10^5 \text{ s}, t_{\text{acc}} \sim 5.6 \times 10^5 \text{ s}, \) and \( t_{\text{p}} \sim 1.7 \times 10^6 \text{ s} \). To model the SED, Tavecchio et al. (2013) considered a lower magnetic field; however, this modeling does not correspond to the HESE-35 event, thus we consider \( B' \sim 1 \) G here. The 2 PeV neutrino event (\( N_\nu = 1 \) must have originated from the inner jet of PKS B1424-418 when the flare was in a very high state corresponding to \( \delta = 2.5 - 2.6 \) and the protons must have accelerated to energy \( E_p \sim 40 \text{ PeV} \). We calculate the neutrino flux at \( E_\nu = 2 \text{ PeV} \) and the integrated flux for two time windows \( T = 288 \) days and \( T = 988 \) days consistent with the flaring period of PKS B1424-418 (Kadler et al. 2016), shown in Table 2. Our model predicts that, during the major outburst period of \( \sim 9 \) months, the \( F_{\nu}(2 \text{ PeV}) \sim (1.6 - 1.9) \times 10^{-10} \text{ erg cm}^{-2} \text{s}^{-1} \).

### 4. Discussion and Conclusions

The temporal and directional coincidence of the high energy neutrino event IceCube-170922A with the flaring blazar TXS 0506+056 in VHE \( \gamma \)-rays as well as in low wavelengths suggests that blazars are strong candidates for at least a fraction of the observed high energy neutrinos and also VHE cosmic rays and \( \gamma \)-rays (Kadler et al. 2016; IceCube Collaboration et al. 2018a). To consistently explain this neutrino event and the multiwavelength electromagnetic emission, particularly the VHE \( \gamma \)-rays observed by MAGIC telescopes, different variants of single-zone leptonic and leptohadronic models are used. Here, we briefly discuss some of these models and their results and compare with our model.

Cerruti et al. (2019) have used the proton-synchrotron and SSC emission with a subdominant but nonnegligible contribution from photodihadronic cascade to explain the neutrino event. They have shown that the proton-synchrotron picture is disfavored due to an insufficient neutrino production rate. On
the other hand, to be compatible with the neutrino event, the lepto-hadronic scenario demands more power in the jet. Similarly, Keivani et al. (2018) have proposed a single-zone hybrid lepto-hadronic scenario and shown that $\gamma$-rays are produced by EIC processes and high energy neutrinos via a radiatively subdominant hadronic component. Here they have argued that, because of the cascade effects, the $0.1–100$ keV emissions of TXS 0506+056 are a better probe for the hadronic components than the GeV–TeV emissions. Yet in another work Ansoldi et al. (2018), based on the spine-sheath model of Ghisellini et al. (2005), have used a single-zone lepto-hadronic scenario where protons and electrons are coaccelerated in the jet and interact with external photons from the slow moving sheath, to explain the neutrino event and observed VHE $\gamma$-rays. Here it is shown that the VHE $\gamma$-rays are mostly from IC upscattering of external photons by accelerated electrons and the 290 TeV neutrino event is of photohadronic origin.

In all these above models, apart from many free parameters, it is difficult to explain the VHE $\gamma$-rays and neutrino events in a single-zone scenario, thus multi-zone scenarios may be required. On the other hand, the photohadronic scenario discussed here assumes a composite jet structure with an inner jet of high photon density encircled by an outer jet of lower photon density with similar bulk Lorentz factors ($\Gamma_{\text{in}} \simeq \Gamma_{\text{ext}} \simeq \Gamma$), and the VHE spectrum can be fitted with a single parameter, the spectral index $\delta$ and the maximum required proton energy is $E_{p} \simeq 20E_{\gamma}$.

Using a photohadronic model, we have shown that the VHE $\gamma$-ray spectrum observed by MAGIC telescopes can be explained very well if the flaring was in a high state. As the 290 TeV neutrino event was observed six days prior to the gamma-ray event, we argued that TXS 0506+056 was in a very high emission state during the neutrino emission period when spectral index $\delta$ was in the range of 2.5–2.6 and subsequently decayed to high and low emission states. For the $\Delta$-resonance to be produced from the $p\gamma$ interaction, we have shown that the different timescales should satisfy Equation (3). As the proton spectral index is taken to be $\alpha = 2$, the power index $\beta$ of the seed photon in the inner jet will be in the range of 0.5–0.6. This shows that the seed photon flux is flatter in the very high state compared to the one in the high/low emission state. It is the power-law distribution of the seed photon background, having a leptonic origin, that decides the nature of the flaring state. So there is a direct correlation between the flaring state and the leptonic origin of the seed photons in the jet. As the maximum energy of the proton depends on the acceleration timescale and the magnetic field, in TXS 0506+056 to produce the 290 TeV neutrino the very high flaring state has to be sustained for about half a day in the presence of $B' \sim 1$ G. A similar situation must also prevail for PKS B1424-418 to produce PeV neutrinos. We took different time windows to estimate the neutrino flux at 290 TeV and found that our results are consistent with the upper limit reported by IceCube and the estimated flux predicted by MAGIC. The same method is used to fit the observed VHE $\gamma$-ray spectrum from PKS B1424-418 and the neutrino flux is estimated.

Although, the IceCube-170922A neutrino event and the flaring of the blazar TXS 0506+056 are found to be correlated, further observation of neutrinos from blazars and follow-up observations in VHE $\gamma$-rays as well as in lower wavelengths are necessary to establish a definitive connection between them.

This will also establish AGN as sources of high energy cosmic rays.

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Software: Modeling and plots were done using the distribution of Python 3.7.2. Packages used include: Matplotlib (Hunter 2007), Numpy (van der Walt et al. 2001), and Scipy (Oliphant 2007). Further calculations were performed using Wolfram Mathematica 12.1 (https://www.wolfram.com/mathematica).

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