Lepto-hadronic γ-Ray and Neutrino Emission from the Jet of TXS 0506+056

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Abstract

The observation of the IceCube-170922A event from the direction of TXS 0506+056 when it was in its enhanced γ-ray emission state offers a unique opportunity to investigate the lepto-hadronic processes in blazar jets. Here, the observed broadband emission of TXS 0506+056 is explained by boosted synchrotron/synchrotron self Compton emission from the jet, whereas the γ-ray data observed during the neutrino emission by inelastic interactions of the jet-accelerated protons in a dense gaseous target. The proton energy distribution is \( \sim E_p^{−2.50} \), calculated straightforwardly from the data obtained by the \textit{Fermi} Large Area Telescope (\textit{Fermi}-LAT) and the Major Atmospheric Gamma Imaging Cherenkov Telescopes (MAGIC); if such a distribution continues up to \( E_p = 10 \text{ PeV} \), the expected neutrino rate is as high as \( \sim 0.46 \) events during the long active phase of the source or \( \sim 0.15 \) if the activity lasts 60 days. In this interpretation, the energy content of the protons above \( \geq \text{GeV} \) in blazar jets can be estimated as well: the required proton injection luminosity is \( \sim 2.0 \times 10^{48} \text{ erg s}^{-1} \), exceeding \( 10^{50} \) times that of electrons \( \sim 10^{48} \text{ erg s}^{-1} \), which are in equipartition with the magnetic field. As the required parameters are physically realistic, this can be an acceptable model for an explanation of the neutrino and γ-ray emission from TXS 0506+056.

\textbf{Key words:} BL Lacertae objects: individual (TXS 0506+056) \– galaxies: jets \– gamma rays: galaxies

1. Introduction

Recently, IceCube detected very high-energy (VHE; \(>100 \text{ GeV} \)) neutrinos from extragalactic sources (Aartsen et al. 2013, 2014; IceCube Collaboration 2013). This opens new perspectives for investigation of nonthermal processes in astrophysical objects, even though no sources emitting these neutrinos have been identified so far. As neutrinos are not absorbed when interacting either with a photon field or the matter, unlike γ-rays, they can be detected from distant sources which are “terra incognita” for γ-ray observations.

Different types of objects are proposed as potential sources for VHE neutrino emission, among which the most prominent are active galactic nuclei (AGNs). AGNs, being powered by supermassive black holes, are among the most luminous and energetic extragalactic objects. When the jet of an AGN is aligned with an observer’s line of sight, they appear as blazars (Urry & Padovani 1995) which, based on the observed emission lines, are commonly subdivided into BL Lacertae (BL Lac) objects and flat-spectrum radio quasars (FSRQs). Blazars are characterized by high luminosity (e.g., \(10^{47}–10^{49} \text{ erg s}^{-1} \)) in the γ-ray band and variable nonthermal emission in the radio to the VHE γ-ray bands. As blazar emission is dominating in the extragalactic energy range, it is natural to consider them as the most probable sources of the observed neutrinos. In fact, Padovani & Resconi (2014), Padovani et al. (2016), have recently found a correlation between high-energy (HE) peaked BL Lac objects (emitting \(>50 \text{ GeV} \)) detected by \textit{Fermi} Large Area Telescope (\textit{Fermi}-LAT) and the VHE neutrino sample detected by IceCube. Also remarkable is the possible association of the highest-reconstructed-energy (\(\sim 2 \text{ PeV} \)) neutrino event with the exceptionally bright phase of FSQ PKS B1414-418 (Kadler et al. 2016). Recently, Aartsen et al. (2017b) showed that the maximum contribution of the known blazars to the observed astrophysical neutrino flux in the energy range between 10 TeV and 2 PeV is less than 27%, but in principle, significant neutrino emission from a particularly bright blazar can be detected.

There are proposed different mechanisms for VHE neutrino production in blazars (e.g., Mannheim 1995; Bednarek 2016; Protheroe 1997; Yoshida et al. 1997; Tavecchio & Ghisellini 2015; Khiali & de Gouveia Dal Pino 2016; Murase et al. 2016; Wang & Liu 2016). These relativistic jets are ideal laboratories where the leptons (electrons) and hadrons (protons) can be effectively accelerated, which when interacting with the magnetic and/or photon fields can produce emission across the whole electromagnetic spectrum. Even if the leptonic emission alone can explain the observed features of some blazars, the energetic protons co-accelerated with electrons might contribute to the observed emission. As the protons probably carry a significant fraction of the total jet power, the exact estimation of their content in the jet is crucial for understanding the jet launching, collimation, and dynamics. In general, only HE γ-ray observations alone are not sufficient to differentiate between the contribution of protons and electrons; this can be done only by neutrino observations.

The lack of a high-confidence association of a neutrino event with a particular blazar significantly complicates the interpretation of hadronic emission from blazar jets. The best association to date is that between IceCube-170922A neutrino event with the γ-ray bright BL Lac object TXS 0506+056 (IceCube Collaboration et al. 2018). The \textit{Fermi}-LAT and the Major Atmospheric Gamma Imaging Cherenkov Telescopes (MAGIC) observations reveal that TXS 0506+056 was in the active state in MeV/GeV and above 100 GeV bands when the neutrino event was observed on 2017 September 22; the evolution of its multiband emission in time around the neutrino event can be seen at \url{youtu.be/IFBcIGIT0mE} (Padovani et al. 2018). At the redshift of \( z = 0.336 \) (Paiano et al. 2018), TXS 0506+056 is among the brightest BL Lac objects detected by \textit{Fermi}-LAT. Moreover, IceCube detected a 3.5σ excess of neutrinos from the direction of TXS 0506+056 in 2014–2015 (IceCube Collaboration 2018). Further detailed spatial and temporal analyses of the complex γ-ray region around TXS 0506+056 showed that the emission from the nearby flaring blazar PKS 0502+049 is dominating at low energies, but TXS...
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The data available from the observations of TXS 0506+056 makes it a unique object for testing the lepto-hadronic emission scenarios in blazar jets. For example, in Ansoldi et al. (2018), the one-zone lepto-hadronic model based on the interaction of both accelerated electrons and protons (photo-meson reaction) with the external photons (from a slow-moving external layer) can successfully explain the observed multiwavelength spectral energy distribution (SED) and neutrino rate if the proton energies are in the range from $10^{14}$ to $10^{18}$ eV. In this and other similar models, it is impossible to estimate the relative contribution of low-energy protons ($>$1 GeV), which carry a significant portion of the jet power. An alternative modeling of the multiwavelength emission from TXS 0506+056 is applied in the current paper; it is assumed that the protons accelerated in the jet of TXS 0506+056 interact with a dense target crossing the jet and produce the observed HE and VHE $\gamma$-ray emission from the decay of neutral pions. This is done within widely discussed jet-target interaction models, which were successfully applied for modeling the emission from different AGNs (e.g., M87, Barkov et al. 2010, 2012b; Cen A core, Araudo et al. 2010; Mrk 421, Dar & Laor 1997; 3C 454.3, Khangulyan et al. 2013, etc.).

The interaction of the blazar jets with clouds or stars pose severe difficulties for one-zone leptonic scenarios; the emission region will be beyond the event horizon of the central black holes only in case of extremely high bulk Lorentz factors (e.g., see Barkov et al. 2012a; Aharonian et al. 2017). Therefor, there have been proposed more complex scenarios: multi-zone models (e.g., spine-sheath, Tavecchio & Ghisellini 2008; decelerating-jet, Georganopoulos & Kazanas 2003; jets in a jet, Giannios et al. 2009, 2010, etc.), and internal-shock models (e.g., Marscher & Gear 1985; Spada et al. 2001; Sokolov et al. 2004; Böttcher & Dermer 2010; Joshi & Böttcher 2011).

The HE component in blazar SEDs can be also explained by applying alternative models invoking the radiative output of hadrons accelerated in the jets of blazars. The protons unavoidably accelerated in jets can interact with matter $pp$, magnetic, or radiation field ($proton-\gamma$) and produce the observed HE emission. In the last two cases, to emit either through proton-synchrotron emission (Aharonian 2000; Mücke & Protheroe 2001) or photo-pion production (Mannheim & Biermann 1992), the protons should be accelerated to extremely high energies ($E_p > 10^{19}\text{eV}$) and propagate in a highly magnetized plasma ($B > 30 \text{G}$). These requirements for the protons and/or the medium can be somewhat softened when a highly collimated proton beam accelerated in the jet penetrates into a dense and compact target (e.g., cloud(s) from BLR Dar & Laor 1997; Beall & Bednarek 1999; Araudo et al. 2010) and produces the observed HE $\gamma$-rays through inelastic $pp$ scattering. In addition, at larger distances from the nucleus rich in star populations, the star–jet interactions too can produce HE $\gamma$-rays (Bednarek & Protheroe 1997; Beall & Bednarek 1999; Barkov et al. 2010; Araudo et al. 2013; Bednarek & Banasiński 2015; de la Cita et al. 2016). In these cases, the protons should be accelerated only up to moderate $\approx 100 \text{TeV}$ energies, unlike in the other models.

2. Broadband Emission from Jets

Dominantly, the emission from blazars is of a nonthermal nature, extending from radio to VHE $\gamma$-ray bands, with two broad humps in the SED, peaking in the IR-X-ray and MeV–TeV bands. This double-peaked feature can be attributed to radiative losses of nonthermal electrons. The low-energy component can be well explained by synchrotron emission of relativistic electrons in the jet and the inverse Compton scattering of soft target photons on these electrons can be responsible for the HE peak. The target photon fields depend mostly on the location of the emission region (Sikora et al. 2009), being of different origin and varying along the jet. For example, for BL Lac objects with very weak (or absent) emission lines, the target photons can be synchrotron photons (synchrotron self Compton, SSC; Ghisellini et al. 1985; Maraschi et al. 1992; Bloom & Marscher 1996), whereas for FSRQs where the jet propagates in an environment reach of protons, the HE component can originate also from inverse Compton scattering of external photons (e.g., photons reflected from broadline region, BLR; Sikora et al. 1994, or from a dusty torus; Błażejowski et al. 2000; Ghisellini & Tavecchio 2009). These models have been successful in explaining several features observed in the nonthermal spectra of blazars, e.g., spectra in different bands, simultaneous or non-simultaneous flux increases (decreases), etc. However, the observation of minute-scale $\gamma$-ray variability of blazars poses severe difficulties for one-zone leptonic scenarios; the emission region will be beyond the event horizon of the central black holes only in case of extremely high bulk Lorentz factors (e.g., see Barkov et al. 2012a; Aharonian et al. 2017). Therefor, there have been proposed more complex scenarios: multi-zone models (e.g., spine-sheath, Tavecchio & Ghisellini 2008; decelerating-jet, Georganopoulos & Kazanas 2003; jets in a jet, Giannios et al. 2009, 2010, etc.), and internal-shock models (e.g., Marscher & Gear 1985; Spada et al. 2001; Sokolov et al. 2004; Böttcher & Dermer 2010; Joshi & Böttcher 2011).

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2.1. The Model

The interaction of the blazar jets with clouds or stars abundant in their environment does not significantly affect the dynamics of the jet and its propagation to kpc scales, but it provides targets for efficient hadronic interactions. The strong shock formed at interaction of relativistic flows with dense targets can accelerate the particles, and in some cases their interactions can be responsible for the steady (e.g., several clouds can interact with the jet simultaneously) or flare-like $\gamma$-ray emissions. The studies of hydrodynamical simulations of jet–target interactions and dynamical timescales required for particle acceleration and emission show that star-target interactions can produce detectable $\gamma$-ray fluxes not only in the nearby (e.g., Cen A, Araudo et al. 2010; M87, Barkov et al. 2010), but also in distant/powerful objects (e.g., 3C 454, Khangulyan et al. 2013; Mrk 421, Dar & Laor 1997; Beall & Bednarek 1999). For a comprehensive and detailed study of the hydrodynamical simulation of jet–cloud/star interactions and discussion of jet stability, see Bosch-Ramon et al. (2012) and Perucho et al. (2017).

The scenarios mentioned above require several parameters for accurate estimation of the duration, rate and efficiency of interactions and the related radiative outputs. The parameters

0506+056 is brighter above a few GeV, making it the most probable neutrino source (Padovani et al. 2018).
Figure 1. Broadband SED of TXS 0506+056 for the active (left) and low VHE γ-ray emitting states. The boosted synchrotron/SSC emission from the jet are shown in gray, whereas the γ-ray spectra from pp interactions and synchrotron emission from secondary e−e+ pairs are shown in blue. The data are corrected for EBL absorption adopting the model from Domínguez et al. (2011).

Figure 2. Same as Figure 1, for TXS 0506+056 during the active (left) and low VHE γ-ray emitting states. The boosted synchrotron/SSC emission from the jet are shown in gray, whereas the γ-ray spectra from pp interactions and synchrotron emission from secondary e−e+ pairs are shown in blue. The data are corrected for EBL absorption adopting the model from Domínguez et al. (2011).

describing the targets (e.g., clouds or stars envelopes) and the energy distribution of accelerated protons are different for each source, but even within the typical values (e.g., clouds with \( \sim 10^{10} - 10^{12} \text{ cm}^{-3} \) density and \( \sim 10^{12} - 10^{15} \text{ cm} \) radius) the powerful jet–target interactions can produce observable γ-ray emission. Another important parameter is the distance (d) from the base of the jet where the interaction occurs. Star–jet/cloud interaction cannot occur within the jet formation region and also at large distances from the central source, as the jet energy flux decreases with the distance as \( F_j \sim L_j / \pi d^2 \) (θ is the jet opening angle). For very powerful jets, the jet energy flux might be still high enough for an effective interaction farther from the jet launching point which will also allow the protons to be accelerated to HEs. On the other hand, for low-power jets, when the penetration occurs in the innermost part of the jet, the protons can be further accelerated in the target, gaining energies required for HE γ-ray emission (Araudo et al. 2010; Barkov et al. 2010). Even though the jet–target interactions can occur frequently, for some jets the observed γ-ray emission is likely to be dominated by boosted SSC emission from jet-accelerated electrons. However, in some cases when the leptons cool faster not reaching HEs or due to some internal changes in the jet affecting only the boosted emission, the hadronic component produced in star–jet interactions can dominate and produce the observed HE and VHE γ-rays. Such scenario can be applied only when γ-ray and neutrino emissions are detected, e.g., from TXS 0506+056.

Since our primary goal is to investigate whether the observed HE and VHE γ-ray and neutrino emission from TXS 0506+056 can be explained by the interaction of moderately accelerated protons and measure their content in the jet, here, without going much in details (e.g., the nature of target, at which distance the interaction occurred, etc.), the broadband SED of TXS 0506+056 obtained during the neutrino event detection is modeled. Assuming that the energetic protons (either accelerated in the jet or in the target) interact in a target with a typical density of \( 10^{10} \text{ cm}^{-3} \), the γ-rays are produced through pp interactions. Most likely, the maximum energy of protons will be defined by the size of acceleration region rather than by radiative losses, i.e., at a rate close to the theoretical limit \( t_{\text{acc}} \sim R/c \). Expressing the acceleration time as \( E/dE/dt \approx \eta Bc \) (Aharonian et al. 2002) is the proton acceleration rate with η efficiency, implies that \( E_{\text{max}} \simeq 3.0 \times 10^{15} (\eta/0.1) (B/1 \text{ G}) (R/10^{13} \text{ cm}) \text{ eV} \). So, even if the proton acceleration occurs in a relatively small \( \sim 10^{13} \text{ cm} \) dense target, \( E \) goes well beyond \( \sim 10 \text{ PeV} \), enough to produce the observed VHE γ-ray photons and neutrino. In the case when the protons are accelerated in the jet, in the frame of the target their energy will be even higher due to Doppler boosting. The protons interacting in the target produce γ-rays from the decay of neutral pions (\( \pi^0 \rightarrow \gamma \gamma \)), while the neutrinos (\( \nu \mu, \nu_e \) are produced from the decay of \( \pi^\pm \) (e.g., \( \pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \nu_\mu + P_0 \)).

The observed γ-ray luminosity of TXS 0506+056 around 10 GeV (most likely the peak of HE component) is \( \sim 4 \times 10^{46} \text{ erg s}^{-1} \), then assuming the efficiency of energy transfer from relativistic protons to secondary particles is \( \sim 10\% \), the required proton luminosity should be \( L_p \approx 4 \times 10^{47} \text{ erg s}^{-1} \). Next, assuming the proton acceleration efficiency is roughly 10%, the jet power would be \( L_{\text{jet}} \approx 4 \times 10^{48} \text{ erg s}^{-1} \) — a value usually estimated for bright blazars. Thus, both the maximum energy of protons and the required luminosity are physically realistic and the observed HE and VHE γ-ray emission from TXS 0506+056 can be due to pp interactions.

3. SED Modeling

The broadband SEDs of TXS 0506+056 for low (period 1 [P1]) and high (period 2 [P2]) VHE γ-ray emitting states (when the neutrino was detected) are shown in Figure 1 (taken from Ansoldi et al. 2018). As compared with the archival data (light gray), (i) the low-energy component is relatively constant and (ii) the HE component slightly increases and the spectrum extends above several hundreds of GeV. This well fits in the scenario discussed above; the synchrotron emission of electrons accelerated in the jet is almost unchanged while most likely a different process is responsible for the HE emission in the active states. It is natural also to expect that the γ-ray flux produced by the same electrons remains the same as the time-averaged one.

The emissions from two different jet regions are considered in the SED modeling: (i) the observed low-energy and time-averaged HE components are explained as emission directly from jet-accelerated electrons in a compact region moving with the bulk Lorentz factor of the jet and (ii) during the active γ-ray emitting state, when the neutrino was observed, the γ-rays are produced from the inelastic pp interactions in the second emission site. Such a compact emitting region is usually considered when modeling the multiwavelength emission from blazars (e.g., Ghisellini et al. 1985; Maraschi et al. 1992; Bloom & Marscher 1996), while the
second zone is expected to form when a target penetrates into the jet (see the sketch in Figure 1 of Bosch-Ramon et al. 2012, where a jet–target interaction is illustrated). Next, the emission from the $e^{-}e^{+}$ pairs produced from the decay of charged pions in the target, which can be significant in the X-ray band, is also taken into account. This modeling allows to estimate both the electron and proton content in the jet. The radiative contribution of electrons is computed within the one-zone scenario, assuming the emission region (the “blob”) is a sphere with a radius of $R$ moving with a bulk Lorentz factor of $\Gamma$, carrying a magnetic field of $B$ and having a population of relativistic electrons with an energy distribution of

$$N_e^*(E_e^*) \sim E_e^{\alpha} \exp \left( - \frac{E_e^*}{E_{\text{cut}}^*} \right)$$  \hspace{1cm} (1)$$

between $E_{\text{min}}^*$ and $E_{\text{max}}^*$ (Inoue & Takahara 1996); $E_{\text{cut}}^*$ is the cutoff energy. As the contemporaneous data from the rising part of the low-energy component are missing, the electron spectral index $\alpha$ cannot be measured, so $\alpha = 2$ expected from acceleration theories is used. Also, $E_{\text{min}}^* = 100$ MeV is used, so the model does not overpredict the archival radio data. The luminosity of the synchrotron emission of these electrons will be amplified by a relativistic Doppler factor of $\delta$ ($\delta = \Gamma$ for small jet viewing angles), for which $\delta = 25$ was used, a characteristic value for bright blazars (Ghisellini & Tavecchio 2015). The observations of TXS 0506+056 in the X-ray, HE and VHE $\gamma$-ray bands allowed to infer a variability timescale of $t_d \lesssim 10^5$ s (e.g., Keivani et al. 2018; Ansoldi et al. 2018) which implies that the emission is produced in sub-parsec regions of the jet, so $R \approx 7.5 \times 10^{16}$ cm will be used. The energy distribution of protons accelerated in the jet can be also expressed as

$$N_p(E_p) \sim E_p^{-\gamma} \exp \left( - \frac{E_p}{E_{\text{cut}}^p} \right),$$  \hspace{1cm} (2)$$

where $E_{\text{cut}}^p$ is first considered as a free parameter, then $E_{\text{cut}}^p = 10^{17}$ PeV is used as the $\gamma$-ray data there is no sign of any spectral cutoff. $\gamma$-rays, neutrinos and $e^{-}e^{+}$ pairs will be produced in the interactions of these protons. The characteristic cooling time of $pp$ collisions is $t_{pp} \approx (K_{\sigma_{pp}}n_\pi)^{-1} \approx 10^{15} n_\pi$, which is inversely proportional to the target particle number density. In case of optimal radiation $t_{pp} \approx t_r$ ($t_r = 5 \times 10^5$ s), the target density is $n_\pi = 10^{10}$ cm$^{-3}$. The size of the emitting target can be estimated as $r = (3M_t t_r/4 \pi n_\pi m_p)^{1/3} \approx 5.2 \times 10^{11} (M_t/10^{23} M_\odot)^{1/3}$ cm (e.g., from Barkov et al. 2010 for the weak tidal disruption). We note that this number density and size are typically estimated for the clouds in BLR (e.g., Netzer 2015; Peterson 2006) and adopted in star-cloud (e.g., Araudo et al. 2010) or star–jet (e.g., Barkov et al. 2010) scenarios. As the target density is high, the protons lose a significant fraction of their energy at $pp$ collisions: the interaction is in a radiatively efficient regime, $t_{pp} \lesssim t_r$, so most of the $\gamma$-rays are emitted around $t_r$ rather than when the target is already accelerated to high velocities. The $\gamma$-ray and neutrino spectra above 100 GeV are calculated using the analytic approximations from Kelner et al. (2006), while the delta function approximation for lower energies is used (for exact formula see Sahakyan et al. 2014). The secondary $e^{-}e^{+}$ pairs spectrum will be similar to that of $\gamma$-rays but shifted to lower energies (see Equation (62) in Kelner et al. 2006). During the fitting (synchrotron/SSC emission of jet-accelerated electrons and $pp$ interactions) the model free parameters are derived by Markov Chain Monte Carlo sampling of their likelihood distributions (Zabalza 2015). This allows to obtain the parameters and their uncertainties which best describe the observed spectra statistically. The following expected ranges are considered: $1.5 \leq \alpha_p \leq 10$, $0.511$ MeV $\leq E_{\text{cut}}^\nu$, $E_{\text{cut}}^p \leq 10$ TeV, and the normalization of electrons/protons and $B$ are defined as positive parameters.

4. Results and Discussions

Detailed temporal and spatial analyses of the complex $\gamma$-ray region around the VHE neutrino event IceCube-170922A illustrates that most likely TXS 0506+056 is the source of the observed VHE neutrinos (Padovani et al. 2018). This is a direct evidence that cosmic rays (protons) are effectively accelerated in the jet of TXS 0506+056. The data available from the multiwavelength observations of TXS 0506+056 around the neutrino event make this source an interesting (unique) object where the HE and VHE processes can be investigated using $\gamma$-rays as well as neutrinos.

The multiwavelength SEDs modeled within the combined leptonic/hadronic scenario are shown in Figure 1. The boosted synchrotron emission from the jet-accelerated electrons can explain the low-energy component, while the SSC radiation of the same electrons—the time-averaged $\gamma$-ray data (solid gray line in Figure 1). During P2, the X-ray photon index measured by Swift XRT is relatively steep ($\Gamma_X > 2.5$), corresponding to the HE tail of synchrotron emission (the gray line in the right panel of Figure 1), allowing us to estimate the cutoff energy at $E_c = 8.90 \pm 0.22$ GeV. The magnetic field energy density is $U_B = 0.88 \times 10^{-3}$ erg cm$^{-3}$ (for $B = 0.15 \pm 0.004$ G) being of the same order as that of the electrons, $U_e = 1.37 \times 10^{-3}$ erg cm$^{-3}$, meaning the system is close to equipartition. During P1, the X-ray flux that most like is produced by a different component, limits the cutoff energy at $E_c = 6.65 \pm 0.21$ GeV and magnetic field to $B = 0.10 \pm 0.002$ G, otherwise the model predicted flux will exceed the observed data. The total jet power in the form of magnetic field and electron kinetic energy calculated as $L_{\text{jet}} = \pi c R_\Delta^2 (U_B + U_e)$ changes in the range of $L_{\text{jet}} = (7.47 - 9.89) \times 10^{43}$ erg s$^{-1}$. The $\gamma$-rays produced from the decay of $\pi^0$ is shown with blue solid and dashed lines in Figure 1. In this case, the slope of proton distribution, $\alpha_p = 2.41 \pm 0.11$ and $\alpha_p = 2.49 \pm 0.07$ for P1 and P2, respectively, is directly measured from the $\gamma$-ray spectra. As the slopes are relatively steep ($\alpha_p \approx 2.5$), most of the proton energy output is at lower energies, so the $\gamma$-ray emission in the GeV band is mostly dominated by the decay of $\pi^0$ with no or a negligible contribution from $e^{-}e^{+}$ pairs from $\pi^0$ decay or $\gamma\gamma$ absorption. When the cutoff energy in Equation (2) is taken as a free parameter, it is constrained by the last point in the $\gamma$-ray data (with largestatistical uncertainty) and corresponds to $E_{\text{cut}}^\nu = 0.98^{+1.45}_{-0.47}$ TeV and $E_{\text{cut}}^p = 4.87 \pm 2.93$ TeV, for P1 and P2, respectively. When $E_{\text{cut}}^\nu = 10$ PeV is considered (blue dashed line in Figure 1), the data can be reproduced when $\alpha_p = 2.54 \pm 0.04$ and $\alpha_p = 2.46 \pm 0.09$ for P1 and P2, respectively. This modeling predicts emission also beyond the MAGIC data, which cannot be tested with the current instruments but certainly it is in agreement with the 100 MeV–400 GeV data. The cutoff
energy $E_{cp} = 10\text{ PeV}$ is an arbitrary value to show that when higher proton energies are considered the data can be reproduced, but cutoff at much higher energies cannot be excluded (for modeling with a hard proton spectrum see Liu et al. 2018).

The modeling of the observed HE and VHE $\gamma$-ray data by $pp$ interactions allows us to estimate the total energy of jet protons—perhaps a large fraction of the total jet power. The data can be reproduced when the total proton energy is $\int E_n N_p(E_n) dE_n \approx (0.97-2.03) \times 10^{53}\text{ erg}$, corresponding to maximum luminosity of $L_p = W_{pp}/t_{pp} \approx 2.0 \times 10^{48}\text{ erg s}^{-1}$. In this case, we note that for the cloud size of $5.2 \times 10^{-13}\text{ cm}$ and a number of density of $10^{10}\text{ cm}^{-3}$, the total energy of target protons is only a small fraction ($\sim 10^{-5}$) of that of jet protons. $W_{pp}$ strongly depends on $n$, which is unknown, and in this case is roughly constrained by the observed flux variation. However, even if it will differ from the used value by two orders of magnitude, the jet luminosity would be still realistic as it is measured in the rest frame. For example, the other hadronic models involving photo-meson interactions the required proton luminosity is much higher (e.g., $L_p \approx 10^{59}\text{ erg s}^{-1}$). The proton luminosity exceeds the power carried by the electrons $\sim 10^5$ times, making a significant contribution to the jet kinetic luminosity. Interestingly, this is similar to the difference between electron and proton luminosities usually estimated assuming one proton per electron. Clearly, both the predicted spectral shapes and the required total energy are physically reasonable, meaning that the $pp$ interactions can solely contribute to the observed HE and VHE $\gamma$-rays.

If the $\gamma$-rays observed from TXS 0506+056 are due to the interaction of protons in the target crossing the jet, secondary $e^- e^+$ pairs will be also produced whose emission can be significant in the X- or $\gamma$-ray bands. As in the target, the magnetic field most likely exceeds that in the jet, e.g., due to higher density of particles; these pairs dominantly will lose energy by synchrotron radiation (a sketch of a jet–target interaction scenario can be seen in Figure 1 of Bosch-Ramon et al. 2012). In this case, the bremsstrahlung energy losses with a cooling time of $t_{be} \approx 10^{16}/(\text{ln}(E_{\gamma}/m_e c^2) + 0.26)\text{ s}$ (Berezinskii et al. 1990) in a completely ionized medium is significantly longer than that of synchrotron emission (for $B \gtrsim 1\text{ G}$). The estimation of the magnetic field in the target is a rather difficult task, depending on the nature of the target, whether it is a cloud or a star envelope. This magnetic field is not necessarily constant, e.g., it can decrease due to expansion of the cloud or increase due to the continuous pumping of jet energy. Possible emission mechanisms when the cloud penetrates into the jet of M87 are discussed in Barkov et al. (2012b). The blue dotted-dashed line in Figure 1 shows the synchrotron emission of secondary $e^- e^+$ pairs in $\sim 80\text{ G}$ magnetic field. At lower energies, the boosted synchrotron emission of electrons directly accelerated in the jet is dominating but due to continuous electron energy losses by synchrotron and SSC radiations, this emission quickly drops already in the X-ray band. Being more energetic, the synchrotron emission from fresh $e^- e^+$ pairs can dominate beyond the X-ray band, reaching HEs. The synchrotron emission of $e^- e^+$ pairs (i) can relatively well explain the X-ray spectrum observed during P1 when $B = 80\text{ G}$ (left panel in Figure 1) and (ii) for the magnetic field $\sim 800$ times stronger than that in the jet, it does not overproduce the data detected by Swift XRT during P2 (right panel in Figure 1) which are most likely due to synchrotron emission of jet electrons. It is interesting that the proton energy required to explain the observed HE and VHE $\gamma$-ray data is also sufficient for transferring enough energy to secondary electrons, so their synchrotron emission can explain the observed X-ray data for a reasonable magnetic field. This strengthens the used hadronic model. However, this X-ray emission in principle might arise also from the synchrotron emission of the secondary pairs produced in the cascades initiated by ultrahigh-energy protons (Ansoldi et al. 2018).

Having calculated the luminosity of protons and their energy distribution, the spectra of HE neutrinos can be calculated straightforwardly and a limit on the expected number of events detectable by IceCube from TXS 0506+056 in a certain exposure time ($t_{exp}$) can be obtained. The neutrinos produced from the protons with an energy distribution of Equation (2) will have a spectrum of $\sim E_{\nu,e}^{-\alpha_{\nu}} \exp(-\sqrt{E_{\gamma}/E_{\nu,c}})$ where $\alpha_{\nu} \approx 0.1$ and $E_{\nu,c} \approx E_{cp}/40$ (Kappes et al. 2007). Therefore, even when $E_{cp} = 10\text{ PeV}$ in the spectrum of neutrinos the cutoff is at $E_{\nu,c} \approx 250\text{ TeV}$, close to the energy of the observed IceCube-170922A event. Next, using the effective area ($A_{eff}(E_{\gamma})$) most sensitive for the location of TXS 0506+056 from Aartsen et al. (2017a), the number of expected events can be estimated as $N_{\nu} \approx t_{exp} \int A_{eff}(E_{\gamma}) d\Phi_{\nu}(E_{\nu}) dE_{\nu}$. This effective area reaches its optimal (maximum) value for neutrino energies above several hundreds of TeV, so to estimate the expected neutrino rates, a significant impact will have the interactions of protons with $E_p \gtrsim 1\text{ PeV}$. The number of expected events is proportional to the duration of the active emission phase of the source. The $\gamma$-ray light curve of TXS 0506+056 calculated above 2 GeV to avoid any bias from the nearby PKS 0502+049 is shown in Figure 5 of Padovani et al. (2018). As one can see, the source was in its active phase around the IceCube-170922A event at least for $t_{exp} > 200\text{ days}$. Indeed, the $\gamma$-ray observations suggest that the active period can be $\sim 0.5–1\text{ year}$ (Ansoldi et al. 2018; IceCube Collaboration et al. 2018; Keivani et al. 2018). Here, we use $t_{exp} = 60\text{ days}$ corresponding to the period when VHE $\gamma$-rays from TXS 0506+056 were observed and $t_{exp} = 0.5\text{ year}$ corresponding to the most prolonged active/bright state of the source. When $E_{cp} = 10\text{ PeV}$, the expected rates during P1 and P2 are $\lesssim 0.04$ and $\lesssim 0.15$ respectively for $t_{exp} = 60\text{ days}$, and $\lesssim 0.13$ and $\lesssim 0.46$, respectively, for $t_{exp} = 0.5\text{ year}$. Yet, assuming the proton acceleration continues beyond 10 PeV or the source active phase is longer, the expected rate would be even higher.

5. Conclusions

In blazar studies, one of the long-standing and unclear questions is whether the protons are effectively accelerated in their jets and if they have a significant contribution to the observed emissions. The $\gamma$-ray observations solely are not sufficient to differentiate between the emission from electrons and protons not allowing to estimate their content in jets exactly. The recent association of TXS 0506+056 with the neutrino events allowed to measure the total energy of the jet carried by electrons and protons.

When the observed $\gamma$-rays and neutrinos from a blazar are due to $pp$ interactions, the energy of protons is mostly released in the GeV band allowing straightforward measurement of the proton spectra based on the observed $\gamma$-ray data. A simplified scenario of lepto-hadronic emission from TXS 0506+056 is
discussed assuming that beside the constant boosted electron synchrotron/SSC emission from the jet compact region, a significant radiation in the γ-ray band is produced when a target (cloud, star envelope, etc.) crosses the jet and the inelastic pp interactions produce pions which then decay into γ-rays. If only the emission from the leptons is considered, the electrons and magnetic field are in equipartition and the observed low-energy and time-averaged γ-ray data can be explained for the jet luminosity of $L_{\text{jet}} \approx 10^{45}$ erg s$^{-1}$. The γ-ray data when the neutrino was observed, can be modeled if the protons are distributed as $\sim E_{p, \gamma}^{-2.50}$ and their energy extends up to $E_{p, \gamma} = 10$ PeV. The expected neutrino rate is 0.13–0.46 during the long active phase of the source and ~0.04–0.15 events if the activity lasts 60 days. The synchrotron emission of electrons directly accelerated in the jet is significant up to the X-ray band, whereas the synchrotron emission of newly injected fresh pairs (from pp interactions) in a dense target dominates afterwards explaining the observed X-ray data obtained during the low VHE γ-ray emission state of TXS 0506+056. Within this scenario, the energy content of the protons (above >GeV) in the blazar jet is estimated for the first time: the required proton injection luminosity should be $\approx 2.0 \times 10^{48}$ erg s$^{-1}$, which exceeds $10^{4}$ times that of electrons. This implies that a significant fraction of the jet kinetic energy is carried by the protons, but still the involvement of hadrons acceleration in the jet will not dramatically (unreasonably) increase its luminosity. Considering the applied model can satisfactorily reproduce the observed multiwavelength emission spectrum of TXS 0506+056 and predicts a sufficient neutrino production rate, it provides an acceptable explanation for the hadronic emission from the TXS 0506+056 jet.

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**References**

Aartsen, M. G., Abbasi, R., Abdou, Y., et al. 2013, PhRvL, 111, 021103
Aartsen, M. G., Abraham, K., Ackermann, M., et al. 2017a, ApJ, 835, 151
Aartsen, M. G., Abraham, K., Ackermann, M., et al. 2017b, ApJ, 835, 45
Aartsen, M. G., Ackermann, M., Adams, J., et al. 2014, PhRvL, 113, 101101
Aharonian, F. A. 2000, NewA, 5, 377
Aharonian, F. A., Barkov, M. V., & Khangulyan, D. 2017, ApJ, 841, 61
Aharonian, F. A., Belyanin, A. A., Derishev, E. V., Kocharovsky, V. V., & Kocharovsky, V. V. 2002, PhRvD, 66, 023005
Ansoldi, S., Antonelli, L. A., Arcaro, C., et al. 2018, ApJL, 863, L10
Araudo, A. T., Bosch-Ramon, V., & Romero, G. E. 2010, A&A, 522, A97
Araudo, A. T., Bosch-Ramon, V., & Romero, G. E. 2013, MNRAS, 436, 3626
Barkov, M. V., Aharonian, F. A., Bogovalov, S. V., Kelner, S. R., & Khangulyan, D. 2012a, ApJ, 749, 119
Barkov, M. V., Aharonian, F. A., & Bosch-Ramon, V. 2010, ApJ, 724, 1517
Barkov, M. V., Bosch-Ramon, V., & Aharonian, F. A. 2012b, ApJ, 755, 170
Beall, J. H., & Bednarek, W. 1999, ApJ, 510, 188
Bednarek, W. 2016, ApJ, 833, 279
Bednarek, W., & Batasiński, P. 2015, ApJ, 807, 168
Bednarek, W., & Protheroe, R. J. 1997, MNRAS, 287, L9
Berezinskii, V. S., Bulanov, S. V., Dogiel, V. A., & Pukin, V. S. 1990, Astrophysics of Cosmic Rays (Amsterdam: North-Holland)
Blazejowski, M., Sikora, M., Moderski, R., & Madejski, G. M. 2000, ApJ, 545, 107
Bloom, S. D., & Marscher, A. P. 1996, ApJ, 461, 657
Bosch-Ramon, V., Peruch, M., & Barkov, M. V. 2012, A&A, 539, A69
Böttcher, M., & Dermer, C. D. 2010, ApJ, 711, 445
Dar, A., & Laor, A. 1997, ApJL, 478, L5
de la Cita, V. M., Bosch-Ramon, V., Paredes-Fortuny, X., Khangulyan, D., & Peruch, M. 2016, A&A, 591, A15
Domínguez, A., Primack, J. R., Rosario, D. J., et al. 2011, MNRAS, 410, 2556
Georganopoulos, M., & Kazanas, D. 2003, ApJL, 594, L27
Ghisellini, G., Maraschi, L., & Treves, A. 1985, A&A, 146, 204
Ghisellini, G., & Tavecchio, F. 2009, MNRAS, 397, 985
Ghisellini, G., & Tavecchio, F. 2015, MNRAS, 448, 1060
Giannios, D., Uzdensky, D. A., & Begelman, M. C. 2009, MNRAS, 395, L29
Giannios, D., Uzdensky, D. A., & Begelman, M. C. 2010, MNRAS, 402, 1649
IceCube Collaboration 2013, Sci, 342, 1242856
IceCube Collaboration 2018, Sci, 361, 147
Mannheim, K. 1995, APh, 3, 295
Mannheim, K., & Biermann, P. L. 1992, A&A, 253, L21
Maraschi, L., Ghisellini, G., & Celotti, A. 1992, ApJL, 397, L5
Marscher, A. P., & Gear, W. K. 1985, ApJ, 298, 114
Mücke, A., & Protheroe, R. J. 2001, ApJ, 151, 121
Muraske, K., Guetta, D., & Ahlers, M. 2016, PhRvL, 116, 071101
Netzer, H. 2015, ARA&A, 53, 365
Padovani, P., Giommi, P., Resconi, E., et al. 2018, MNRAS, 480, 192
Padovani, P., & Resconi, E. 2014, MNRAS, 434, 474
Padovani, P., Resconi, E., Giommi, P., Arsioli, B., & Chang, Y. L. 2016, MNRAS, 457, 3582
Paiano, S., Falomo, R., Treves, A., & Scarpa, R. 2018, ApJL, 854, L32
Peruch, M., Bosch-Ramon, V., & Barkov, M. V. 2017, A&A, 606, A40
Peterson, B. M. 2006, in Physics of Active Galactic Nuclei at all Scales, Vol. 693, ed. S. Alloin (Berlin: Springer), 77
Protheroe, R. J. 1997, in ASP Conf. Ser. 121, IAU Coll. 163, Accretion Phenomena and Related Outflows, ed. D. T. Wickramasinghe, G. V. Bicknell, & L. Ferrario (San Francisco, CA: ASP), 585
Sahakyan, N., Piano, G., & Tavani, M. 2014, ApJ, 780, 29
Sikora, M., Begelman, M. C., & Rees, M. J. 1994, ApJ, 421, 153
Sikora, M., Stawarz, Ł., Moderski, R., Nalewajko, J., & Madejski, G. M. 2009, ApJ, 704, 38
Sokolov, A., Marscher, A. P., & McHardy, I. M. 2004, ApJ, 613, 725
Spada, M., Ghisellini, G., Lazzati, D., & Celotti, A. 2001, MNRAS, 325, 1559
Tavecchio, F., & Ghisellini, G. 2008, MNRAS, 385, L98
Tavecchio, F., & Ghisellini, G. 2015, MNRAS, 451, 1502
Urry, C. M., & Padovani, P. 1995, PASP, 107, 803
Wang, X.-Y., & Liu, R.-Y. 2016, PhRvD, 93, 083005
Yoshida, S., Dai, H., Jui, C. C. H., & Sommers, P. 1997, ApJ, 479, 547
Zabalza, V. 2015, ICRC (The Hague), 34, 922

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