A self-consistent leptonic-hadronic interpretation of the electromagnetic and neutrino emissions from blazar TXS 0506+056

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Abstract

The potential association between the blazar TXS 0506+056 and the neutrino event IceCube-170922A provides a unique opportunity to study the possible physical connection between the high-energy photons and neutrinos. We explore the correlated electromagnetic and neutrino emissions of blazar TXS 0506+056 by a self-consistent leptonic-hadronic model, taking into account particle stochastic acceleration and all relevant radiative processes self-consistently. The electromagnetic and neutrino spectra of blazar TXS 0506+056 are reproduced by the proton synchrotron and hybrid leptonic-hadronic models based on the proton-photon interactions. It is found that the hybrid leptonic-hadronic model can be used to better explain the observed X-ray and $\gamma$-ray spectra of blazar TXS 0506+056 than the proton synchrotron model. Moreover, the predicted neutrino spectrum of the hybrid leptonic-hadronic model is closer to the observed one compared to the proton synchrotron model. We suggest that the hybrid leptonic-hadronic model is more favored if the neutrino event IceCube-170922A is associated with the blazar TXS 0506+056.

Key words: BL Lacertae objects: individual( TXS 0506+056 ) – galaxies: active – galaxies: gamma-ray – neutrino – radiation mechanisms: non-thermal

1 Introduction

Neutrino observation by IceCube has opened up a new window in the study of nonthermal processes in astrophysical objects. However, the sources responsible for the neutrino emission have not been identified so far. As the neutrinos are not absorbed when interacting with the background photons or the matters, they can be detected even though the source is far away. The observed distribution of their arrival direction suggests a predominantly extragalactic origin. Extragalactic sources, such as active galactic nuclei (Murase et al. 2014; Petropoulou 2015; Padovani 2016; Gao et al. 2017), $\gamma$-ray burst (Murase et al. 2006; Petropoulou 2014) and supernova (Murase et al. 2011; Petropoulou 2017), have been proposed as the potential high-energy neutrino sources. Blazars are believed to be the most promising candidate sources with high-energy neutrino emission.

The IceCube observation recently reported the detection of a neutrino event (IceCube-170922A ), which is coincidence with the blazar TXS 0506+056 during its flaring state (IceCube Collaboration 2018a; IceCube Collaboration 2018b). Following the neutrino alert, the blazar TXS 0506+056 is detected in a multi-wavelength campaign, ranging from the ra-
dio to γ-ray bands (IceCube Collaboration 2018b). The multi-
wav length observations characterize the polarization, variabil-
ity and energy spectrum of the blazar TXS 0506+056. This
source is also first detected in very high-energy γ-ray bands
with the MAGIC Cherenkov telescopes. A chance coincident
of the high-energy neutrino with multi-wavelength flare is re-
jected at a 3.5 σ level. The potential association between the
activity of TXS 0506+056 and the neutrino event suggests that
this object could be the counterpart of the neutrino event.

Blazars are a subclass of radio-loud active galactic nu-
clei powered by supermassive black holes. Their radiation is
thought to originate in a relativistic jet oriented at a small
angle with respect to the line of sight. Blazars are often classified into
BL Lac objects and flat spectrum radio quasars (FSRQs). BL
Lacs have weak or absent emission lines, while FSRQs usually
show strong broad emission lines. The spectrum energy dis-
tributions (SEDs) of blazars are characterized by non-thermal
continuum spectra with a broad low-energy component from
radio-UV to X-ray and a broad high-energy component from
X-ray to γ-ray. It is generally accepted that the low-energy
component of blazar SEDs is produced by synchrotron emis-
tion from relativistic electrons accelerated in the jet of blazar.
The high-energy component is often interpreted as the inverse
Compton (IC) upscattering of ambient soft photons by the ac-
celerated electrons (e.g., Böttcher 2007). The soft photons can be
either synchrotron photons within the jet (the synchrotron
self-Compton, SSC, process, Maraschi et al. 1992; Bloom and
Marscher 1996), or the photons external to the jet (the External
Compton, EC, process). These external photons may be the UV
accretion disk photons (Dermer & Schlickeiser 1993), the ac-
cretion disk photons reprocessed by broad-line region clouds
(Sikora et al. 1994), or infrared photons from the dust torus
(Błażejowski et al. 2000). The above scenario is called the
leptonic model. Such models have achieved great successes in
explaining the multi-wavelength emission and variability from
blazars (Böttcher 2002; Weidinger & Spanier 2010).

It is physically plausible that the protons are co-accelerated
with the electrons to very-high energy by the same mechanism
in the jet of blazar. In the so-called hadronic model, the
synchrotron emission from the high-energy proton can dominate
the high-energy component in the SED of blazars (Mannheim
1993; Mücke et al. 2003). Moreover, the high-energy protons
can interact with the background photons to produce the sec-
ondary electrons, the synchrotron emission from the secondary
electrons can have a significant contribution to the high-energy
component (Petroploulou & Mastichiadis 2012; Mastichiadis et
al. 2013; Cerruti et al. 2015; Weidinger & Spanier 2015; Diltz
& Böttcher 2016; Zech et al. 2017). The high-energy com-
ponent can also be produced by the π⁰ decay from the proton-
photon(pγ) interactions (Sahu et al. 2013; Cao & Wang 2014).
For a recent review on blazar hadronic modelling, see Böttcher
et al. (2013).

IceCube observation implied that the blazar TXS 0506+056
could be a high-energy neutrino source. The neutrinos are gen-
erally associated with the hadronic processes in the jet of blazar.
High-energy neutrinos can be produced by the decay of charged
pions from the pγ interaction. Therefore, the neutrinos can be
considered as the unique signature of these hadronic interac-
tions. The recent study revealed that the multi-TeV gamma-rays
of blazars can be well explained by the photohadronic process,
which provides a strong evidence that the neutrino emission
from blazars may originate in the photohadronic process (Sahu
et al. 2019). In this paper, we study the correlated electromag-
etic and neutrino emissions of blazar TXS 0506+056 by a self-
consistent leptonic-hadronic model, taking into account both
electrons and protons stochastic acceleration and all relevant
radiative processes self-consistently. We reproduce the elec-
tromagnetic and neutrino emissions of blazar TXS 0506+056
by the proton synchrotron and hybrid leptonic-hadronic models
based on the pγ interaction. We demonstrate that the observed
neutrino signature can allow us to distinguish these different
emission models.

In Section 2 we give a brief description of the model. In
Section 3 we apply the model to explain the electromagnetic
and neutrino emissions of blazar TXS 0506+056. The dis-
cussion and conclusion are presented in Section 4. Throughout
this paper, we adopt the cosmological parameters of $H_0 = 70$
k m s⁻¹ Mpc⁻¹, $\Omega_M = 0.3$, $\Omega_{\Lambda} = 0.7$.

2 model

2.1 Model geometry

In this section, we give a brief description of the model intro-
duced by Weidinger & Spanier (2015). We improve the model
of Weidinger & Spanier (2015) by implementing the kinetic
equation of the neutrinos and the Bethe-Heitler process. For a
detail description about the model, see Weidinger & Spanier
(2010); Weidinger & Spanier (2015).

The model assumes a spherical geometry with two zones,
where a acceleration zone with radius $R_{\text{acc}}$ is nested within
a larger radiation zone with a radius $R_{\text{rad}}$. Both zones are
assumed to be homogeneous and to contain isotropic elec-
tron and proton distributions as well as a randomly oriented
magnetic field. The considered blob travels down the jet axis
towards the observer with a bulk Lorentz factor $\Gamma$, the upstream
material is picked up into the acceleration zone where a highly
turbulent zone is formed at the edge of the blob. Here, both
injected particle species are subjected to stochastic acceleration
processes up to the relativistic energies balanced by their
radiation losses. However, the acceleration is assumed to be
inefficient in the considerable larger radiation zone. The kinetic
equations for each particle species $i$ in each zone can be derived from the relativistic Vlasov equation (Schlickeiser 2002) by one-dimensional diffusion approximation using the relativistic approximation $p_i = m_i c$. Since blazar jets are almost aligned with the line of sight of the observer, we assume the Doppler factor $\delta \simeq \Gamma$. All calculations are conveniently made in the rest-frame of the blob.

### 2.2 Kinetic equation in the acceleration zone

As the blob propagates through the jet, the particles from the upstream of jet are injected into the acceleration zone with an injected function

$$Q_{0.i}(\gamma) = Q_{0,i} \delta(\gamma - \gamma_{0,i}),$$

(1)

where we assume a mono-energetic and time-independent injection. Each injected particle species are continuously accelerated up to very-high energies by stochastic acceleration processes with the synchrotron and SSC losses. The energy gain due to the acceleration is balanced by the radiative and escape losses. In the acceleration zone, a hard-sphere approximation is used to describe the plasma instabilities, hence the spatial diffusion coefficient $K_{\parallel,i}$ is independent of particle energy (Schlickeiser 1989; Stawarz & Petrosian 2008). This allows one to find the characteristic acceleration timescales due to stochastic acceleration processes $t_{acc,i} = v_{A,i}^2/4K_{\parallel,i}$ (Weidinger & Spanier 2010; Weidinger & Spanier 2015), where $v_A$ is Alfvén speeds. We assume the acceleration timescale to be constant and scale linearly with the particles mass. The timescale of the second species can be naturally obtained by relation $t_{acc,i} \propto m_i$. Moreover, the escape timescale is set to be constant and proportional to the acceleration timescale $t_{esc,i} \propto t_{acc,i}$. We expect that the stochastic acceleration produces a power-law spectrum with spectral index $q \simeq 1 + t_{acc} / (2 t_{esc})$. This differs from the spectral index $q \simeq 1$ with shock acceleration, which may be expected from the observed SEDs from blazars (e.g., Katarzyński et al. 2006; Kakwu et al. 2015; Diltz & Böttcher 2016; Gao et al. 2017). In this paper, we focus on the possibility of the stochastic acceleration in blazar jets.

We assume that the acceleration zone cannot directly produce the observed SEDs, hence we only solve the kinetic equations for the primary particles. The kinetic equations for primary electrons and protons are given by (Katarzyński et al. 2006)

$$\partial_t n_i = \partial_\gamma \left[ \left( P_{s,i}(\gamma) + P_{IC,i}(\gamma) - t_{acc,i}^{-1} \gamma \right) \cdot n_i \right]$$

$$+ \partial_\gamma \left[ \left( 2 t_{acc,i} \right)^{-1} \gamma^2 \partial_\gamma n_i \right] + Q_{0,i} - \frac{n_i}{t_{esc,i}}.$$  

(2)

Where $P_{IC,i}(\gamma)$ is the inverse-Compton loss of each particle species, $P_{s,i}(\gamma)$ is the synchrotron loss of each particle species with

$$P_{s,i}(\gamma) = \frac{4}{3} \frac{c \sigma_T}{m_e c^2} u_B \left( \frac{m_e}{m_i} \right)^3 \gamma^2 = \beta_{s,i} \gamma^2,$$

(3)

where $\sigma_T$ is the Thomson cross section, $u_B = \frac{B^2}{8\pi}$ is the energy density of the magnetic field.

### 2.3 Kinetic equation in the radiation zone

As every escaping particle from the acceleration zone enters the radiation region, the particle spectrum $n_i(\gamma)$ from the acceleration zone sever as the injection function of the radiation zone. The particles are not accelerated in the radiation zone. Therefore, all relevant cool processes have to be taken into account, including synchrotron, inverse-Compton and photihadronic losses. The kinetic equations for electrons, protons, photons, secondary positrons and neutrinos are solved self-consistently and time-dependently.

The low-energy photons from the primary electrons and protons are soft photons for the $\gamma\gamma$ interactions. When the proton energy is above the threshold for the $\gamma\gamma$ interactions, the high-energy protons will interact with the jet soft photons to produce secondary particles by the two channel:

The photon-pair production (Bethe-Heitler process)

$$p + \gamma \rightarrow e^+ + e^- + p.$$  

(4)

and the photon-meson production (see, e.g., Romero & Vila 2008; Kelner & Aharonian 2008)

$$p + \gamma \rightarrow p + a \pi^0 + b(\pi^+ + \pi^-),$$

$$p + \gamma \rightarrow n + \pi^+ + a \pi^0 + b(\pi^+ + \pi^-).$$  

(5)

Where $a$ and $b$ are the pion multiplicities. The produced pions are unstable particles, they decay into stable electrons, positrons, neutrinos and $\gamma$-ray photons by the channel:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu,$$

$$\pi^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu,$$

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu,$$

$$\pi^- \rightarrow e^- + \nu_e + \bar{\nu}_\mu,$$

$$\pi^0 \rightarrow \gamma + \gamma.$$  

(6)

This process will result in the third contribution to the VHE peak in the SEDs of blazars, besides the proton synchrotron emission and inverse-Compton emission from relativistic electrons. We use the Kelner & Aharonian (2008) parametrization of the SOPHIA Monte Carlo results to calculate the production rate of the stable electrons, positrons, neutrinos and $\gamma$-ray photons by the interactions of equation (6). We note that the decay timescale of unstable products from the $\gamma\gamma$ interactions is shorter compared to the synchrotron loss timescale. Therefore, we do not account for the synchrotron losses and radiation of the intermediate particles ($\mu^\pm, \pi^\pm$).

The proton kinetic equation in the radiation zone is given by
Fig. 1. Predicted multwavelength flux and neutrino flux of TXS 0506+056 for the proton synchrotron model. The red circles are the observed multi-wavelength data and the green circle is the detected neutrino flux from IceCube observation. The black dashed curves represent the synchrotron emission and the SSC emission, respectively (from left to right). The blue dashed curves represent the proton synchrotron emission, the synchrotron emission from the secondary pairs and the $\gamma$-ray emission from $\pi^0$ decay, respectively (from left to right). The cyan dashed curves represent the synchrotron emission of the secondary pairs from the Bethe-Heitler process. The green dashed curve represents the muon neutrino spectrum from the charged pions decay. All flavor neutrino spectrum is also shown as the green solid curve. The red solid curve is the total spectrum from all emission components, while the red dashed curve is the EBL-corrected spectrum using the EBL model of Finke et al. (2010). For comparison, The EBL-corrected spectrum using the EBL model of Franceschini et al. (2008) is also shown as the red dotted curve. The observed data are taken from IceCube Collaboration (2018b).

Fig. 2. Proton, electron and positron spectra from the derived SEDs in figure 1.
\[ \partial_t N_p = \partial_t \left[ \left( P_{s,p}^{\gamma \gamma}(\gamma) + P_{\gamma SN}(\gamma) + P_{\gamma B}(\gamma) \right) N_p \right] + \frac{N_p}{t_{esc,p} - t_{esc,rad,p}} \]

\[ b = \left( \frac{R_{acc}}{R_{rad}} \right)^3 < 1 \]

where \( b \) is a geometric factor ensuring particle conservation. We use the formula given by Kelner & Aharonian (2008) to calculate the proton losses due to the photon-meson interaction \( P_{\gamma \gamma}^{\gamma \gamma}(\gamma) \). The proton losses from the Bethe-Heitler process \( P_{\gamma B}(\gamma) \) is calculated using the formula given by Begelman et al. (1991). As in the acceleration zone, the escape timescale is assumed to scale with the particle’s mass, e.g., \( t_{esc,rad,p} \propto m_p \), derived from the particle’s light crossing time of a sphere with radius \( R_{rad} \), multiplied by a constant empirical factor \( \eta = 10 \).

The \( \gamma \)-rays from the \( \pi^0 \) decay and the secondary \( e^\pm \) synchrotron emission are partially in the optically thick regime. The high-energy \( \gamma \)-ray photons can interact with the low-energy synchrotron photons to produce the secondary pairs by

\[ \gamma + \gamma \rightarrow e^+ + e^- . \]

This process will initiate an electromagnetic cascade until the radiation enters the optically thin regime. The secondary pairs from the \( \gamma \gamma \) interactions serve as an additional injection term in the kinetic equations of electron and positron.

The kinetic equations for the electrons and positrons in the radiation zone are thus given by

\[ \partial_t N_{e^-} = \partial_t \left[ \left( P_{s,e}^{\gamma \gamma}(\gamma) + P_{IC}^{\gamma \gamma}(\gamma) \right) N_{e^-} \right] - \frac{N_{e^-}}{t_{rad,esc,e^-}} + Q_{\gamma \gamma}(\gamma) + Q_{\gamma \gamma}(\gamma) + Q_{\gamma \gamma}(\gamma) + b \frac{N_p}{t_{esc,e^-}} , \]

\[ \partial_t N_{e^+} = \partial_t \left[ \left( P_{s,e}^{\gamma \gamma}(\gamma) + P_{IC}^{\gamma \gamma}(\gamma) \right) N_{e^+} \right] - \frac{N_{e^+}}{t_{rad,esc,e^+}} + Q_{\gamma \gamma}(\gamma) + Q_{\gamma \gamma}(\gamma) + Q_{\gamma \gamma}(\gamma) . \]

Table 1. Model parameters of the proton synchrotron process

| Parameters | Value |
|-----------|-------|
| \( B \) (G) | 10 |
| \( \delta_D \) | 48 |
| \( \gamma_0,\gamma \) | \( 6.0 \times 10^3 \) |
| \( Q_{0,\gamma} \) (cm\(^{-3}\) s\(^{-1}\)) | \( 1.6 \times 10^{-1} \) |
| \( Q_{0,\gamma} \) (cm\(^{-3}\) s\(^{-1}\)) | \( 4.0 \times 10^{-3} \) |
| \( R_{acc} \) (cm) | \( 3.0 \times 10^{13} \) |
| \( R_{rad} \) (cm) | \( 1.6 \times 10^{16} \) |
| \( t_{acc}/t_{esc} \) | 1.05 |

The kinetic equation for the photon field in the radiation zone is given by

\[ \partial_t N_{ph} = R_{\gamma}(\nu) + R_{\gamma}(\nu) + R_{\gamma}(\nu) - \frac{N_{ph}}{t_{esc,ph}} \]

where \( t_{esc,ph} = 4R_{rad}/3c \) is the photon escape timescale. The synchrotron production rate \( R_{\gamma} \) and the absorption coefficient \( a_{SSA} \) is calculated using the exact formula given by Finke et al. (2008). The inverse-Compton production rate \( R_{\gamma} \) is calculated using the full Klein-Nishina cross section given by Blumenthal & Gould (1970). The \( \gamma \)-ray production rate from the \( \pi^0 \) decay, \( R_{\gamma} \), is calculated using \( \Phi_{\gamma} \)-parameters of Kelner & Aharonian (2008). The photon annihilation coefficient \( a_{\gamma\gamma} \) is calculated using the exact result of Coppi & Blandford (1990).

The neutrinos are not subject to any interaction except their production and escape. Therefore, the kinetic equation for the neutrinos are given by

\[ \partial_t N_\nu = R_\nu(\nu) - \frac{N_\nu}{t_{esc,ph}} \]

where the production rates for all flavor neutrinos, \( R_\nu(\nu) \), are calculated using the results of Kelner & Aharonian (2008).

To model the observed SEDs of blazar, we need to transform the SEDs from the blob frame to that in the observer frame. The SEDs in the observer frame are given by

\[ \nu F_\nu^{\text{obs}}(\nu, t_{\text{obs}}) = \frac{h \cdot \nu^2 \cdot N_{ph}(\nu, t) \cdot \delta^2 \cdot V_\nu}{4\pi d_L^2 \cdot t_{esc,ph}} \]

with \( \nu_{\text{obs}} = \delta \nu \) and \( \Delta t_{\text{obs}} = \Delta t / \delta \).

2.4 Numeric method

To obtain the model SEDs, we numerically solve a set of the coupled kinetic equations in the acceleration and radiation zone. In the acceleration zone, we use the method of Chang & Copper (1970) to solve the equations (3). In the radiation zone, we use the method of Chiaberge & Ghisellini (1999) to solve the equations (7), (9) and (10). The equations (11) and (12) are solved using the Crank-Nicolson method (Crank & Nicolson 1996). We carefully tested our numerical code with some analytical solutions and found very good agreement.

3 Result

The blazar TXS 0506+056 is a bright BL Lac objects. The redshift of the source was recently measured to be \( z = 0.337 \) (Paiano et al. 2018). In September 2017, the IceCube reported...
Fig. 3. Same as Figure 1, but for the hybrid leptonic-hadronic model.

Fig. 4. Proton, electron and positron spectra from the derived SEDs in figure 3.
Table 2. Model parameters of the leptonic-hadronic process

| Parameters          | Value          |
|---------------------|----------------|
| $B$ (G)             | 0.95           |
| $\delta_D$          | 28             |
| $\gamma_0,e$        | $1.5 \times 10^3$ |
| $Q_{0,e}$ (cm$^{-3}$ s$^{-1}$) | $1.8 \times 10^{-1}$ |
| $\gamma_0,p$        | $10^2$         |
| $Q_{0,p}$ (cm$^{-3}$ s$^{-1}$) | $1.4 \times 10^{-3}$ |
| $R_{acc}$ (cm)      | $1.0 \times 10^{14}$ |
| $R_{rad}$ (cm)      | $5.5 \times 10^{15}$ |
| $t_{acc}/t_{esc}$   | 1.2            |

A very-high-energy muon neutrino event (IceCube-170922A), which was identified by the Extremely High Energy track event selection. The best-fit reconstructed direction is 0.1° from the sky position of the BL Lac object TXS 0506+056. The energy of the neutrino event is estimated to be 290 TeV with the 90% confidence level lower limits of 183 TeV and upper limits of 4.3 PeV, by assuming a power-law neutrino spectrum with the spectral index of -2. The blazar TXS 0506+056 is a γ-ray source included in the third Fermi-LAT catalog of sources (Acero et al. 2015). Following the IceCube alert, the Fermi-LAT reported that the direction of IceCube-170922A is coincident with the location of TXS 0506+056 and coincident with a state of the γ-ray flare (Tanaka et al. 2017). The follow-up observations were performed by a multi-wavelength campaign with different telescopes, including a significant detection by MAGIC telescopes at > 100 GeV. X-ray emissions by Swift/XRT and NuSTAR, optical emissions by the ASAS-SN survey as well as emission in radio band by VLA (see IceCube Collaboration 2018b ). The high-energy neutrino originates in the hadronic interactions providing a natural link between high-energy γ-rays and neutrino. The combined multi-wavelength and neutrino observations provide a unique opportunity to study the hadronic processes in blazar jets.

We use the model described in section 2 to model the electromagnetic and neutrino spectra of blazar TXS 0506+056. The observed data is taken from IceCube Collaboration (2018b). We interpret the electromagnetic and neutrino spectra of blazar TXS 0506+056 by proton synchrotron and hybrid leptonic-hadronic models. In figure 1, we show the predicted electromagnetic and neutrino spectra for the proton synchrotron model. The modeling parameters are listed in table 1. The derived SEDs are corrected for the EBL absorption using the model of Franceschini et al. (2008) and Finke et al. (2010). The different EBL models predict a similar γ-ray spectrum and the differences between the two EBL models are negligible. It can be seen that the optical and Swift X-ray spectra are produced by the synchrotron radiation of the primary electron, the NuSTAR X-ray spectrum comes from the low-energy tail of proton synchrotron radiation, the high-energy γ-ray spectrum is dominated by proton synchrotron radiation. In fact, the contribution of the secondary emission from the pair cascades to the γ-ray spectrum is negligible due to strong EBL absorption above $10^{20}$ Hz. We note that the SSC emission from the primary electrons and the synchrotron emission of the secondary pairs from the Bethe-Heitler process have a negligible contribution to the observed SEDs due to high magnetic field of $\mathcal{O}(10^7)$ G (see table 1). The peak energy of the predicted neutrino spectrum is $\sim 10^{32}$ Hz, which is far above the observed neutrino energy. In figure 2, we show the proton, electron and positron spectra from the derived SEDs in figure 1. The acceleration zone, the stochastic acceleration process produces a power-law proton injected spectrum with index $q_p \simeq 1 + t_{acc,p}/(2t_{esc,p}) = 1.525$. In the radiation zone, the proton synchrotron loss dominates over the photo-meson loss due to high magnetic field. Therefore, the synchrotron cooling results in a power-law proton spectrum with index $n_p \simeq q_p + 1 = 2.525$ above the break energy $\gamma_{b,p} \simeq 1/(t_{esc,rad,p} \beta_{s,p}) = 5 \times 10^8$. The maximum proton energy can be determined by $\gamma_{max,p} \simeq 1/(t_{esc,p} \beta_{s,p}) = 2 \times 10^9$. The peak energy of proton synchrotron radiation is $\nu_{\max,p} \simeq 4.2 \times 10^{22} \delta B \left(m_e/m_p\right)^{5/3} = 5 \times 10^{24}$ Hz, which is comparable with the value from the model-derived SED (see figure 1). The electron density with $\gamma > 10^4$ is the contribution of the secondary electrons from the pair cascade processes, because the primary electrons can not be accelerated to such high energies. We note that the X-ray and γ-ray data can not be well reproduced by the proton synchrotron model.

In figure 3, we show the predicted electromagnetic and neutrino spectra for the hybrid leptonic-hadronic model. In figure 4, we show the proton, electron and positron spectra from the derived SEDs in figure 3. The modeling parameters are listed in table 2. It can be seen that the optical and Swift X-ray spectra come from the synchrotron radiation of the primary electron. The NuSTAR X-ray spectrum is produced by the combination of the SSC radiation and the synchrotron radiations of the secondary pairs from the Bethe-Heitler processes. The high-energy γ-ray spectrum comes from the combination of the SSC radiation and the synchrotron radiation from the secondary pairs. We note that the synchrotron radiation from the secondary pairs mainly contributes to the high-energy tails of the γ-ray spectrum. In fact, the proton synchrotron radiation makes a negligible contribution to the observed SEDs due to low magnetic field of $\mathcal{O}(1)$ G (see table 2). The neutrino peak energy can be estimated by the maximum proton energy from the relation of $E_\nu = 0.05 E_{\max,p}$. Therefore, the corresponding neutrino peak frequency is $\nu_{\max} \simeq 3 \times 10^{29} (\gamma_{max,p}/10^8)^2 / (\delta/28)$ Hz, which is closer to the observed neutrino energy compared to the proton synchrotron emission. Recently, the study of MAGIC collaboration showed that the blazar TXS 0506+056 has a Doppler factor about 40 (Ansoldi et al. 2018). We also show the predicted
Fig. 5. Same as Figure 3, but for different Doppler factor. The solid curves represent the predicted electromagnetic and neutrino spectrum for the high Doppler factor ($\delta = 40$). For comparison, the predicted electromagnetic and neutrino spectra for the low Doppler factor ($\delta = 28$) are also shown as the dashed curves.

Table 3. Model parameters of the leptonic-hadronic process for the high Doppler factor

| Parameters       | Values               |
|------------------|----------------------|
| $B$ (G)          | 1                    |
| $\delta_D$       | 40                   |
| $\gamma_{0,e}$   | $1.5 \times 10^3$    |
| $Q_{0,e}$ (cm$^{-3}$ s$^{-1}$) | $5.6 \times 10^{-2}$ |
| $\gamma_{0,p}$   | $10^2$               |
| $Q_{0,p}$ (cm$^{-3}$ s$^{-1}$) | $2.3 \times 10^{-3}$ |
| $R_{\text{acc}}$ (cm) | $1.0 \times 10^{14}$ |
| $R_{\text{rad}}$ (cm) | $2.5 \times 10^{15}$ |
| $t_{\text{acc}}/t_{\text{esc}}$ | 1.3                   |

electromagnetic and neutrino spectra for the high Doppler factor ($\delta = 40$) as the solid curves in figure 5. The modeling parameters are listed in table 3. For comparison, the predicted electromagnetic and neutrino spectra for the low Doppler factor ($\delta = 28$) are also shown as the dashed curves. It is found that the model of the high Doppler factor predicts a slightly higher neutrino flux than one of the low Doppler factor. Our results implied that the hybrid leptonic-hadronic model can better match the X-ray and $\gamma$-ray spectra than the proton synchrotron model (see figure 1 and 5).

4 Discussion and Conclusions

The $pp$ interactions have been invoked to explain the observed neutrino spectrum of Blazar TXS 0506+056 (Liu et al. 2018; Wang et al. 2018; He et al. 2018; Sahakyan 2018). The $pp$ interaction usually requires the high plasma density which is not expected in the environment of BL Lac objects due to small accretion rate (Aharonian 2000). The observed neutrino spectrum can be explained by the $p\gamma$ interactions with an external radiation field (Keivani et al. 2018). It is thought that BL Lac objects are lack of a strong external radiation field due to the clean environment around the jet. A steady leptonic-hadronic model was used to study the electromagnetic and neutrino emissions of blazar TXS 0506+056 (Cerruti et al. 2018; Zhang et al. 2018). However, these model do not include the particle acceleration and the relevant radiative processes self-consistently.

In this paper, we study the correlated electromagnetic and neutrino emission of blazar TXS 0506+056 by a self-consistent leptonic-hadronic model, taking into account both electron and proton acceleration and all relevant radiative processes self-consistently. We reproduce the electromagnetic and neutrino spectra of blazar TXS 0506+056 by the proton synchrotron and hybrid leptonic-hadronic models based on the $p\gamma$ interaction. We find that the hybrid leptonic-hadronic model can better reproduce the observed multi-wavelength SEDs of blazar TXS 0506+056. Moreover, the predicted neutrino spectrum of the hybrid leptonic-hadronic model is closer to the observed one compared to the proton synchrotron model. Therefore, we suggest that the hybrid leptonic-hadronic model is more preferred if the neutrino IceCube-170922A originates from blazar TXS 0506+056. It is not possible to put a strong constrain on neutrino production models with single observed neutrino event. Further multi-messenger observations will be needed to understand the possible physical connection between the neutrino and $\gamma$-ray emissions.
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