Lepto-hadronic single-zone models for the electromagnetic and neutrino emission of TXS 0506+056

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ABSTRACT
While active galactic nuclei with relativistic jets have long been prime candidates for the origin of extragalactic cosmic rays and neutrinos, the BL Lac object TXS 0506+056 is the first astrophysical source observed to be associated with some confidence (∼3σ) with a high-energy neutrino, IceCube-170922A, detected by the IceCube Observatory. The source was found to be active in high-energy gamma-rays with Fermi-LAT and in very-high-energy gamma-rays with the MAGIC telescopes. To consistently explain the observed neutrino and multi-wavelength electromagnetic emission of TXS 0506+056, we investigate in detail single-zone models of lepto-hadronic emission, assuming co-spatial acceleration of electrons and protons in the jet, and synchrotron photons from the electrons as targets for photo-hadronic neutrino production. The parameter space concerning the physical conditions of the emission region and particle populations is comprehensively explored for scenarios where the gamma-rays are dominated by either 1) proton synchrotron emission or 2) synchrotron-self-Compton emission, with a minor but non-negligible contribution from photo-hadronic cascades in both cases. We find that the latter provides acceptable solutions, while the former is strongly disfavoured due to the insufficient neutrino production rate.

Key words: BL Lacertae objects: individual: TXS 0506+056– gamma rays: galaxies – neutrinos – radiation mechanisms: non-thermal

1 INTRODUCTION

Ice Cube Collaboration et al. (2018) recently reported the detection of a high-energy neutrino (IceCube-170922A) with the IceCube Observatory with good angular resolution, for the first time coinciding spatially and temporally with a blazar in an elevated γ-ray flux state. A chance correlation is rejected at the 3σ level. The blazar in question, TXS 0506+056, is a high-frequency-peaked BL Lac object, and a known emitter of high-energy γ-rays (Acero et al. 2015). During the multi-wavelength campaign triggered by the IceCube alert (Ice Cube Collaboration et al. 2018; Ahnen et al. 2018), it was seen by Fermi-LAT to be in a high state that began in April 2017 and lasted several months, and was also discovered in very-high-energy (VHE; E > 100 GeV) γ-rays with the MAGIC Cherenkov telescopes. The redshift of the source was recently measured to be z = 0.337 (Paiano et al. 2018). There is currently no estimate on the mass of the central black hole.

While the probability of 56.5% quoted by Ice Cube Collaboration et al. (2018) for this single neutrino to be truly astrophysical does not yet firmly establish blazars as sources of high-energy neutrinos, this detection represents the first direct observational indication for such a link. Earlier attempts to find correlations between high-energy neutrinos and blazars suffered from insufficient angular resolution of the recorded neutrino events and the absence of simultaneous flares. One earlier study (Kadler et al. 2016) claimed a correlation between an IceCube “cascade” event with an energy of 2.0 ± 0.2 PeV, with an angular resolution of 16°, and a high flux state of a blazar of the flat-spectrum radio quasar (FSRQ) type at a confidence level of ∼ 2σ. Lucarelli et al. (2017) also reported tentative evidence of a γ-ray precursor flare detected (at 4σ) with AGILE in coincidence with an IceCube neutrino, but again the significance of the association remained marginal. The 3σ association of IceCube-170922A with a γ-ray flare from TXS 0506+056 thus represents the most significant

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2 NUMERICAL SIMULATIONS

The LeHa code (Cerruti et al. 2015) is used to simulate electromagnetic and neutrino emission from TXS 0506+056. It has been developed to describe the stationary γ-ray emission from BL Lacertae objects, taking into account all relevant leptonic and hadronic radiative processes. We briefly summarize here the main features of the code.

The emitting region is a spherical plasmoid in the relativistic jet, parametrized by its radius $R$ and moving with Doppler factor $\delta$ with respect to the observer. The plasmoid is filled with a tangled, homogeneous magnetic field $B$, and a stationary population of leptons and hadrons, whose energy distributions are parametrized as broken power-law functions with exponential cut-offs. The leptonic part of the code is an extension of the work described in Katarzyński et al. (2001) and includes synchrotron and synchrotron-self-Compton (SSC) radiation by primary leptons. The hadronic part of the code simulates $p$-$\gamma$ interactions, and calculates the radiative output from all secondary particles. Photo-meson interactions are calculated using the Monte-Carlo code SOPHIA (Mücke et al. 2000), while Bethe-Heitler pair-production (not included in SOPHIA) is calculated using the analytical formulae of Kohler & Aharonian (2005). Photons from $\pi^0$ decay, secondary leptons from $\pi^0$ decay and Bethe-Heitler pair-production, can trigger synchrotron-supported pair-cascades in the emitting region. In LeHa, the low-energy photon field that serves as targets for $p$-$\gamma$ interactions as well as $\gamma$-$\gamma$ pair-production is provided by synchrotron radiation by primary leptons, by primary protons and the SSC.

The fact that the parameter space of blazar hadronic models is much larger than that of leptonic models, together with the numerical challenges of correctly simulating hadronic interactions, make the search for best-fit solutions computationally prohibitive. We follow here the approach described in Cerruti et al. (2015) to reduce the number of free parameters via physically motivated a priori assumptions. The number of free parameters of the model is 15: three for the emitting region ($\delta$, $B$, and $R$), six for the primary population of leptons (the indices of the broken power-law distribution, $\alpha_{e,1}$ and $\alpha_{e,2}$; the minimum, break, and maximum Lorentz factors $\gamma_{e,\text{min}}$, $\gamma_{e,\text{break}}$, $\gamma_{e,\text{max}}$; and the normalization $K_e$), and six for the primary population of protons ($\alpha_{p,1}$, $\alpha_{p,2}$, $\gamma_{p,\text{min}}$, $\gamma_{p,\text{break}}$, $\gamma_{p,\text{max}}$, and $K_p$). We impose the following constraints:

- assuming a common acceleration mechanism for the primary leptons and hadrons, we fix the spectral indices of the particle populations to be $\alpha_{e,1} = \alpha_{p,1}$ at injection;
- the primary leptons lose energy mostly via synchrotron radiation, which imposes $\alpha_{e,2} = \alpha_{e,1} + 1$, and $\gamma_{e,\text{break}}$ is determined by equating the synchrotron cooling time-scale $\tau_{\text{syn}}$ with the adiabatic expansion time-scale $\tau_{\text{rad}} = 2R/c$;
- the minimum Lorentz factor of the proton distribution $\gamma_{p,\text{min}}$ is fixed to be 1, since its impact on the models is minor, as long as its value is not too large;
- the same holds for the minimum Lorentz factor of the electron distribution $\gamma_{e,\text{min}}$ which, however, cannot be arbitrarily low, in order not to overshoot archival radio data, and has been fixed to be 500;
- the maximum proton Lorentz factor $\gamma_{p,\text{max}}$ is calculated by equating the acceleration time scale, parametrized as $\tau_{\text{acc}} = \eta_{\text{acc}} \tau_{\text{rad}} / f_p$, and the shortest energy loss time scale for the protons. Constraints from the high-energy peak position on $\gamma_{p,\text{max}}$ are thus translated into constraints on the parameter $\eta$ that controls $\tau_{\text{acc}}$:
- the proton distribution is considered to be a simple power-law without a spectral break, as their energy losses are typically insignificant below $\gamma_{p,\text{max}}$;
- the observed variability time scale $\tau_{\text{var}}$ measured to be of the order of one day by MAGIC, is used to constrain the...
radius of the emission region as \( R \leq \frac{\delta}{\eta} \), following the usual light-travel time argument.

The number of free parameters is thus reduced to eight: \( \delta \), \( B \), and \( R \) for the emitting region, with \( R \) limited via the variability timescale; and \( K_e \), \( K_p \), \( \gamma_{e,max} \), \( \eta e \equiv \eta p \), and \( \eta \) for the particle distributions. \( K_e \) and \( \gamma_{e,max} \) are adjusted to fit the low-energy SED component. The parameter space of the remaining six parameters is studied separately for the two scenarios under investigation, the proton synchrotron one, and the mixed lepto-hadronic one. For each model we compute a posteriori the \( \chi^2 \) with respect to the data, identify the solution with the lowest \( \chi^2 \), and select all models which are characterized by a \( \Delta \chi^2 \) equal to 1 or 2. It should be pointed out that the available radio data cannot be reproduced with any of the solutions discussed here, due to synchrotron self absorption, and are thus associated with a more extended region in the relativistic jet, as is the case for all one-zone blazar models.

The neutrino spectrum is extracted for each (anti-) neutrino flavor and propagated to the observer frame. As usual, it is assumed that the total neutrino flux is distributed equally among the three flavours due to neutrino oscillations. The estimated muon neutrino flux is then convolved with the effective area for the IceCube EHE trigger (Ice Cube Collaboration et al. 2018) to estimate the detection rate.

2.1 Proton synchrotron solutions

In a first approach, we ascribe the high-energy peak of the SED to proton-synchrotron emission, with sub-dominant contributions from synchrotron-pair cascades. As \( \gamma_{p,max} \) is defined by equating the acceleration and cooling time-scales, there exists a maximum proton-synchrotron peak frequency \( \nu_{max} \), for a given choice of \( \delta \) and \( \eta \). We initially set \( \eta = 10 \) as in Cerruti et al. (2015). For the maximum allowed values of \( \nu_{peak,p} \), the energy of the proton-synchrotron peak is always too high compared with the data. Lowering \( \nu_{peak,p} \) leads to a denser emission region with a larger contribution from cascades. Adjusting the peak energy to agree with the data, without over-predicting the VHE and hard X-ray emission due to the cascade component, requires an increase in the value of \( \eta \), i.e. a lower efficiency of the acceleration process.

The transition between the low-energy and high-energy component in the SED is well constrained by the combination of the Swift/XRT and NuSTAR data. A large contribution of the cascade component to the NuSTAR band is disfavoured, as it would invariably overproduce the VHE emission due to its broad spectral coverage. The only alternative is to adjust the spectral slope of the primary particle spectrum so that the proton-synchrotron component dominates the SED all the way from the NuSTAR band up to the high-energy peak. The index of the primary particle distributions is thus fixed to a value of 2.0.

In this scenario, the electrons are in the fast-cooling regime. Given the constraint on the co-acceleration of leptons and hadrons, the large value of the spectral index for particles injection leads to strong electron-synchrotron flux in the optical and infrared range. We have also attempted to find a solution where the high-energy emission is dominated by Bethe-Heitler cascades, but the broad energy distribution of this component is incompatible with the observations.

These various constraints imply a well defined region in the parameter space. We scanned the following range of parameters: \( \delta \in [20 - 50] \), with seven bins linearly spaced; \( R \in [10^{15} \text{cm} - R_{max}] \), with ten bins logarithmically spaced; \( \nu_{peak,p} \in [\nu_{max}/1000, \nu_{max}] \) with ten bins logarithmically spaced; \( \eta \in [10, 50] \), with five bins linearly spaced; and \( K_p \in [K^*/3, 3K^*] \), with five bins logarithmically spaced, where \( K^* \) corresponds to the proton density such that the peak of the proton synchrotron component is at the level of the Fermi-LAT data. In total we produce 17590 different models, and as described above, we use the \( \chi^2 \) to identify 1σ contours for the different parameters, as listed in Table 1.

Allowing for values of \( \delta \) up to 50, solutions within the 1σ confidence region were found for \( B = 0.8 - 32 \text{G} \) and \( R = 10^{15} - 10^{17} \text{cm} \). No satisfactory solutions were found with \( \delta < 35 \). The jet power required for this scenario can vary from \( 8 \times 10^{45} \) to \( 1.7 \times 10^{48} \text{erg s}^{-1} \), increasing with \( R \). The solutions with the lowest power are thus well below the Eddington luminosity of a \( 10^9 \) solar mass black hole. The ratio of energy densities in protons to magnetic fields is \( u_p/u_B = 1 - 89 \), being closer to equipartition for lower total power.

The neutrino spectra for the proton-synchrotron solutions are shown in Fig. 1a. Their shapes are narrow, typically peaking above \( 10^{18} \text{eV} \). The expected detection rates vary widely among the different solutions, yielding a muon neutrino rate between \( 6 \times 10^{-3} \) and 0.2 per year. When restricting the estimate to the reported 90% uncertainty on the energy of IceCube-170922A (183 TeV-4.3 PeV), the rate drops significantly to between \( 2.4 \times 10^{-5} \) and \( 1.7 \times 10^{-3} \). For the highest neutrino rate, the Poisson probability of detecting one neutrino with an energy compatible with that measured by IceCube during the 6-month high state of the source is 0.085%. The probability of not detecting any event outside of this energy range over the same period is 82%.

2.2 Mixed lepto-hadronic solutions

In an alternative approach, we interpret the high-energy emission as a combination of SSC emission and synchrotron radiation from the proton induced cascades, thus probing a very different region in parameter space, with notably smaller values of \( B \). In this mixed lepto-hadronic scenario, the proton-synchrotron peak is hidden below the other components, and protons are limited to lower energies than in the proton-synchrotron scenario. The higher proton density in this scenario is expected to lead to a higher flux of neutrinos peaking at lower energies.

It is possible to interpret the broadband emission, apart from the radio band, with a standard SSC model. Thus, we can only provide an upper limit on the hadronic contribution in the lepto-hadronic scenarios. When assuming a minimum electron Lorentz factor \( \gamma_{e,min} \) of a few hundred, the NuSTAR data can no longer be ascribed to SSC emission, but are accounted for by the cascade component. These data thus serve as upper limits to the hadronic component.

The index of the primary particle distributions is fixed to 2.0 as for the proton-synchrotron solutions, but in this parameter range the lepton population is not completely cooled as in the proton synchrotron scenario. To ease the study of the parameter space, we limit our solutions to the
are inferred, indicating the energetics to be far out of synchrotron solutions. A denser proton population is needed about 40 R spaced; ν while the lower but flatter cascade emission spectrum is re-
SSC emission is largely dominating the high-energy peak, the modelling of the high-energy spectrum and the resulting tions, while verifying that there is no significant impact on be applicable to the mixed lepto-hadronic scenario, we have maximum electron energy) in the primary electron spectrum. when allowing for a detectable cooling break (above the min-
a small region of parameter space with δ = 10.5, large intermediate jet power. Detection rates of more than 0.5 yr−1 can be attained even with a jet power close to the minimum value. When restricting the estimate to the 90% uncertainty on the reported energy of IceCube-170922A, the detection rate is 0.008–0.11. For the solution that provides the highest neutrino rate, the Poisson probability for detecting one νμ with the energy measured by IceCube during the high-state is 5.2%, while the probability for not detecting any events outside of the reconstructed energy interval is 5.5%.

3 DISCUSSION
The probability of detecting a muon neutrino with energy inside the reported 90% confidence interval of IceCube-170922A during the six-month high state of the TXS 0506+056 is sufficiently high for the lepto-hadronic scenario, but only marginal (8.5 × 10−3) for the proton-synchrotron case. The non-detection of neutrinos with higher energies during the same period does not significantly constrain the scenarios. It should be noted, however, that the uncertainty on the energy of IceCube-170922A is large and probabilities for detecting a neutrino increase rapidly, when allowing for higher upper limits on the neutrino energy, due to the steeply increasing neutrino fluxes with energy expected in both scenarios.

The available data set is very constraining for one-zone models, thanks to the good multi-wavelength coverage from the optical to the VHE range. One-zone SSC solutions with standard parameters can be found. While proton-synchrotron solutions are subject to degeneracy between R and B as found in earlier studies, the mixed lepto-hadronic solutions cover relatively small regions in the B−R parameter space that would indicate an emitting region of typical extension 1016 cm and a location at sub-parsec distance from

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Figure 1. Modeling of TXS 0506+056 for the proton synchrotron (1a) and lepto-hadronic (1b) scenarios. Black dots represent data from Ice Cube Collaboration et al. (2018), while gray points are archival data. For each model, bold lines represent the total emission in photons (below 100 TeV) and neutrinos (above 100 TeV); dashed lines the emission from pion cascades; dotted lines the emission from Bethe-Heitler cascades; dotted-dashed lines the proton synchrotron emission. Colours from red to blue represent increasing values of R.
the central engine for typical jet opening angles. As is usually found for (lepto-)hadronic models, the required jet power is relatively high and largely dominated by that in protons. Solutions in the proton-synchrotron scenario are generally less demanding in this respect, and one can find parameter sets likely corresponding to sub-Eddington luminosity. It is important to underline that our solutions are characterized by $\alpha_{p,1} = 2.0$ and $\gamma_{p,\text{min}} = 1$, and are thus conservative in terms of the total power in hadrons. A lower luminosity can be achieved if $\gamma_{p,\text{min}} \geq 1$ or $\alpha_{p,1} \leq 2.0$. Lower luminosities can also be achieved if the photons that serve as targets for $p\gamma$ interactions originate outside the jet (see Ahnen et al. 2018).

The two scenarios should in principle be distinguishable with future variability studies of this source. While the lepto-hadronic scenario predicts a strong correlation between the low-energy and high-energy spectral bumps, as in any SSC scenario, the proton-synchrotron scenario would imply delays between variations in the two components due to the different acceleration and cooling time scales. A delay is also expected between the hard X-ray component and the high-energy peak flux in the lepto-hadronic solutions. In both scenarios, the time-averaged SED during the high state of the source is well reproduced by the model, while a rapid flux increase over a few nights, potentially seen in the VHE band, would require time-dependent modelling. The stationary solutions presented here are however consistent with a variability time scale of one day.

In the proton-synchrotron scenario, protons can reach a maximum Lorentz factor of $10^5$, close to the highest observed energies of ultra-high-energy cosmic rays, when taking into account Doppler boosting. Maximum proton energies are low by a factor of ten in the lepto-hadronic scenario, but the proton density is much higher.

### 4 CONCLUSIONS

After introducing a few simplifying constraints based on general physical considerations, we have explored the full parameter space of the lepto-hadronic one-zone model for the spectral energy distribution of the 2017 high state of TXS 0506+056. Good solutions can be found with the proton-synchrotron and mixed lepto-hadronic scenarios in strongly disfavoured if the Ice Cube event 179022A has its origin in the source, lepto-hadronic solutions can account for this event, while being relatively more demanding in terms of the jet power. If a second neutrino detection was detected from this source, this strongly favour the lepto-hadronic scenario, while the absence of any future neutrino detections could be used to put constraints on the acceptable parameter space for both scenarios.

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The luminosity of the emitting region has been calculated as

$$L = 2\pi R^2 c \Gamma_{\text{bulk}} (u_B + a_e + u_p),$$

where $\Gamma_{\text{bulk}} = \delta/2$, and $u_B$, $a_e$, and $u_p$, the energy densities of the magnetic field, the electrons, and the protons, respectively. The quantities flagged with a star (*) are derived quantities, and not model parameters.

### Table 1. Parameters used for the hadronic models

| Parameter | Proton-synchrotron | Lepto-hadronic |
|-----------|---------------------|----------------|
| $z$       | 0.337               | 0.337          |
| $\delta$  | 35 – 50             | 30 – 50        |
| $R \, [10^{24} \text{ cm}]$ | 0.1 – 9.7 | 0.2 – 1.5 |
| $\tau_{\text{obs}} \, [\text{days}]$ | 0.01 – 1.0 | 0.02 – 0.3 |
| $B$       | 0.8 – 32             | 0.13 – 0.65    |
| $u_B \, [\text{erg cm}^{-3}]$ | $0.02 – 0.16$ | $6.5 \times 10^{-4} – 0.017$ |

| Parameter | Proton-synchrotron | Lepto-hadronic |
|-----------|---------------------|----------------|
| $\gamma_{p,\text{min}}$ | 500               | 500            |
| $\gamma_{p,\text{max}}$ | $= \gamma_{p,\text{min}}$ | $= \gamma_{p,\text{max}}$ |
| $\alpha_{e,1}$ | $= \alpha_{p,1}$ | 2.0            |
| $\alpha_{e,2}$ | $= \alpha_{p,2}$ | 3.0            |
| $K_e \, [\text{cm}^{-3}]$ | $6.3 – 9.1 \times 10^9$ | $9.5 \times 10^5 – 2.6 \times 10^6$ |
| $u_e \, [\text{erg cm}^{-3}]$ | $0.4 – 15.1$ | $2.2 \times 10^3 – 4.3 \times 10^3$ |
| $\gamma_{p,\text{break}}$ | $= \gamma_{p,\text{max}}$ | $= \gamma_{p,\text{max}}$ |
| $\eta$ | 0.4 – 2.5 | 0.06 – 0.2 |
| $K_p \, [\text{cm}^{-3}]$ | $10.4 – 2.0 \times 10^9$ | $3.5 \times 10^8 – 6.6 \times 10^9$ |
| $u_p \, [\text{erg cm}^{-3}]$ | $0.7 – 45$ | $100 – 1400$ |
| $\gamma_{p,\text{break}} \, [10^9 \text{ erg s}^{-1}]$ | $1.0 – 89$ | $3.9 \times 10^9 – 7.9 \times 10^9$ |
| $v_{183-430 \text{ TeV}} \, [\text{year}^{-1}]$ | $2.4 \times 10^{-3} – 1.7 \times 10^{-3}$ | $0.008 – 0.11$ |

$\nu^{\gamma} \, [\text{year}^{-1}]$ | $5.7 \times 10^{-3} – 0.2$ | $0.11 – 3.0$ |

The luminosity of the emitting region has been calculated as

$$L = 2\pi R^2 c \Gamma_{\text{bulk}} (u_B + a_e + u_p),$$

where $\Gamma_{\text{bulk}} = \delta/2$, and $u_B$, $a_e$, and $u_p$, the energy densities of the magnetic field, the electrons, and the protons, respectively. The quantities flagged with a star (*) are derived quantities, and not model parameters.

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