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Neutrinos from interactions between the relativistic jet and large-scale structures of BL Lac objects investigated through their gamma-ray spectrum

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Absorption and emission lines in the optical spectrum are typically used to investigate the presence of large-scale environments in active galactic nuclei (AGNs). BL Lac objects - which are a category of AGNs with the relativistic jet pointing directly to the observer - are supposed to represent a late evolution stage of AGNs. Their large-scale structures are probably poorer of material, which is distributed with lower densities throughout the circumnuclear environment. Their accretion disk is weak and weakly reprocessed, making the non-thermal continuum of the relativistic jet dominate their optical spectrum and preventing us from identifying the thermal emission of the photon fields produced by such large-scale structures. However, these photon fields may still exist and eventually interact with the gamma rays traveling in the blazar jet via gamma-gamma pair production, producing observable effects such as absorption features in their spectral energy distribution. Interestingly, the same photon field might also lead to the production of high-energy neutrinos, acting as targets for proton-photon interactions. In this contribution, we present the results of a set of simulations over a wide parameter space describing both the blazar jet and the photon field properties. We discuss the most effective conditions that may produce fluxes of neutrinos compatible with the sensitivities of the current and the next generation of neutrino detectors. We will also discuss how the possible neutrino flux would be related to the properties of the large-scale structures investigated indirectly through the analysis of the gamma-ray spectrum of the BL Lac object.

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1. Introduction

Blazars are a category of active galactic nuclei (AGNs) that emit relativistic jets pointing towards the line-of-sight of the observer. Among them, BL Lac objects are blazars where the thermal components are overwhelmed by the non-thermal radiation of the jet, which emits through the whole electromagnetic spectrum and enters deeply the gamma-ray energy band. The presence of large-scale structures of the AGN environment is usually investigated through the presence of ambient photon fields emitting in its optical spectrum. However, in BL Lac objects also this thermal emission is usually hidden by the non-thermal continuum of the relativistic jet, and emission lines are faint or not present at all.

An alternative method to investigate the possible presence of large-scale structures around BL Lac environments has been suggested by Foffano et al. [5], where we developed an alternative technique that may unveil the presence of large-scale structures through the analysis of the BL Lac gamma-ray spectra. In that scenario, we considered the relativistic jet of a BL Lac object passing through a dense photon field produced by the large-scale structures of the blazar, for example a narrow-line region (NLR). If gamma rays are produced before such a dense target photon field, their observed flux will be severely affected (or even completely suppressed) by the $\gamma\gamma$ interaction $\gamma_{\rm jet} + \gamma_{\rm target} \rightarrow e^+ + e^-$ [for more details see 1], following

$$I_{\rm out} = I_{\rm in}\, e^{-\tau_{\gamma\gamma}} \ ,$$

where $I_{\rm out}$ and $I_{\rm in}$ are respectively the observed and the original flux of gamma rays . The absorption factor $\tau_{\gamma\gamma}$ of the $\gamma\gamma$ interaction - assuming a mono-energetic, isotropic, and uniform seed photon field - can be expressed as a function of the cross-section $\sigma_{\gamma\gamma}(E)$, of the size of the interacting region R, and of its photon density $n_{\rm seed}$: $\tau_{\gamma\gamma} = n_{\rm seed} \cdot R \cdot \sigma_{\gamma\gamma}(E)$. Specifically, we define the target photon column density $K_{\rm seed} = n_{\rm seed} \cdot R$, which is a critical parameter describing the target photon field and that is related to the strength of the absorption process. In the case of typical AGN photon fields with energies ranging from infrared to optical and UV, the $\gamma\gamma$ interactions produce the strongest absorption at gamma rays, making this process indirectly visible by our gamma-ray detectors. This process is being investigated with a systematic analysis of the gamma-ray spectra of numerous BL Lac objects. Interestingly, the most promising sources where this effect could be easily detectable are high-peaked BL Lac objects (HBLs) and extreme HBLs (EHBLs, or *extreme blazars*, e.g. Costamante et al. [3], Foffano et al. [4]), which are BL Lac objects defined on the basis of their synchrotron peak frequency $\nu_{\rm peak}^{\rm sync}$ lying between 10^{15} and 10^{17} Hz for HBLs and above $\nu_{\rm peak}^{\rm sync} > 10^{17}$ Hz for EHBLs. Thanks to their strong and uncontaminated emission up to TeV energies, they offer the best spectra to investigate the presence of gamma-ray absorption features.

2. Neutrino production in BL Lac objects

In this work, we pursue the scenario assumed in Foffano et al. [5] by considering that the presence of large-scale structures in BL Lac objects may also lead to the production of high-energy neutrinos, acting as targets for proton-photon interactions. We will consider mainly photo-meson interactions between the protons accelerated in the jet and the photons emitted by the large-scale structure. If jets contain hadrons (protons and light nuclei), they will inevitably interact with the same NLR photons that absorbs TeV gamma rays: the detection of absorption features in gamma rays can thus be used to constrain this photon field and provide an estimate of the target for hadronic interactions.

The photo-meson (or photo-pion) process is the production of pions in proton-photon interactions [2]:

$$p + \gamma \rightarrow p_0 + \pi_0 \qquad p + \gamma \rightarrow n + \pi^+ \qquad p + \gamma \rightarrow p_0 + \pi^+ + \pi^- \ .$$

For astrophysical applications we mostly consider the production of neutral and charged pions, which can happen when the photon energy in the proton rest frame is higher than 145 MeV. Pions decay into leptons (muons and electrons/positrons) and neutrinos following

$$\pi_0 \rightarrow \gamma\gamma \qquad \pi^\pm \rightarrow \mu^\pm + \nu_\mu(\bar{\nu}_\mu) \rightarrow e^\pm + \nu_e(\bar{\nu}_e) + \nu_\mu + \bar{\nu}_\mu \ .$$

A crucial aspect of photo-meson reactions is that the product is composed by neutrinos and photons together. Interestingly, neutrinos can escape from the emitting region without being affected by absorption effects. Then, detecting neutrinos and photons together from an AGN may be a smoking-gun signal for the presence of relativistic protons accelerated in the jet, making AGNs possible accelerators of protons to high energies and consequently a possible source of cosmic rays detected at Earth [e.g. 6].

3. Method

In this work, we are computing the neutrino production rate and the neutrino spectrum [following e.g. 7] given by the interaction between the relativistic jet of the BL Lac object and the possible photon fields produced by its large-scale structures. Parameters of the model are related both to the physical conditions of the relativistic jet and to the properties of the target photon field.

The main parameters of the relativistic jet are usual properties describing the blazar emitting region, such as the bulk Lorentz factor Γ, the magnetic field B, the radius r, the proton acceleration efficiency η, the proton energy distribution, and the redshift of the source z. Conversely, the photon field is currently being simulated with any possible optical spectra that may be produced by a large-scale structure like a NLR.

A set of simulations spanning over the whole parameter space is being addressed, aiming at discussing how the possible neutrino flux would be related to the properties of the large-scale structures investigated indirectly through the analysis of the gamma-ray spectrum of the BL Lac object, and finally discussing the most effective conditions that may produce fluxes of neutrinos compatible with the sensitivities of the current and the next generation of neutrino detectors.

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