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Lepto-Hadronic Multimessenger Modelling of Markarians 421 and 501

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Abstract. Active galactic nuclei (AGN) are galaxies whose nucleus emits a large amount of energy in the non-thermal spectrum. These astrophysical objects are among the most energetic phenomena in the Universe. Numerous subclasses of AGN have been defined based on their observed characteristics. Among them are blazars, which emit relativistic jets pointed at Earth. These jets are beams of ionized matter accelerated to near the speed of light, which radiate energetically across the entire electromagnetic spectrum. To model the radiation emission spectrum of blazars through the radioactive processes of relativistic charged particles, as well as their hadronic interactions that occur within the jet, allow us to derive the spectral distribution of non-thermal energy from these sources, to infer information about the mechanisms of particle acceleration in the source, investigate the composition of the jet and finally determine whether the source is a possible emitter of ultra-energetic neutrinos. In this work, a leptohadronic modeling of the blazar sources, Markarian 421 and Markarian 501, the latter located in the constellation of Hercules and the former in the constellation of Ursa Major, is performed in order to study the spectral distribution of energy with multiple interactions, leptonic and hadronic, using a numerical modeling software called AM^3.

Resumo. Núcleos ativos de galáxias (AGN) são galáxias, cujo o núcleo emite uma enorme quantidade de energia com espectro não térmico. Estes objetos astrofísicos estão entre os fenômenos mais energéticos do Universo. Numerosas subclasses de AGN foram definidas com base em suas características observadas. Dentre elas temos os blazares, que emitem jatos relativísticos orientados na direção da Terra. Estes jatos são feixes de matéria ionizada acelerados perto da velocidade da luz, os quais irradiam energeticamente através de todo espectro eletromagnético. Modelar o espectro de emissão de radiação de blazares através dos processos radioativos de partículas carregadas relativísticas, bem como suas interações hadrônicas que ocorrem no interior do jato, nos permite derivar a distribuição espectral de energia não térmica destas fontes, para inferir informações sobre os mecanismos de aceleração de partículas na fonte, investigar a composição do jato e por fim determinar se a fonte é uma possível emissora de neutrinos ultra energéticos. Neste trabalho é feita uma modelagem leptohadrônica das fontes blazares, Markarian 421 e Markarian 501, esta localizada na constelação de Hércules e aquela na constelação na constelação de Ursa Major, com o intuito de estudarmos a distribuição espectral de energia com múltiplas interações, leptônicas e hadrônicas, utilizando-se de um software de modelagens numérica denominado AM^3.

Keywords. Galaxies: active – Neutrinos – BL Lacertae objects: Individual: Markarians – Radiation mechanisms: non-thermal

1. Introduction

Markarians 421 and 501 are a subclass of active galactic nuclei (AGN) characterized by their extreme variability, high-energy emissions, and jets closely aligned with our line of sight, making their emissions highly Doppler-boosted and variable. They are both critical laboratories for studying jet physics, particle acceleration, and the interplay between synchrotron and gamma-ray emissions in AGN. Both sources exhibit a double-peaked spectral energy distribution (SED), characteristic of blazars. The lower-energy peak is attributed to synchrotron radiation from electrons in the jets, while the higher-energy peak likely arises from inverse Compton scattering of photons by these electrons (Synchrotron self-Compton (SSC) model; Acciari et al 2010, Albert et al. 2022). This work aims to model the SEDs of Markarians 421 and 501 via leptonic interactions and to investigate the possibility of a contribution coming from proton-photon and proton-proton interactions to describe the very high energy gamma-ray emission.

1.1. Markarian 421

Markarian 421 (Mrk 421) is the closest known blazar located in the constellation Ursa Major, at a distance of about 397 million light-years. Mrk 421 exhibits emission across the electromagnetic spectrum, including radio, optical, X-ray, and gamma rays. Observations from instruments like the High Altitude Water Cherenkov (HAWC) Observatory[1] (Albert et al. 2022) and VERITAS[2] reveal that Mrk 421 emits gamma rays up to several TeV (Binks 2010).

1.2. Markarian 501

Markarian 501 (Mrk 501) is one of the closest and brightest extragalactic sources of very-high-energy (VHE) gamma rays, located at a distance of approximately 456 million light-years in the constellation Hercules. Observations from instruments such as VERITAS, MAGIC, and the Fermi Gamma-ray Space Telescope have provided detailed studies of its variable gamma-ray and X-ray emissions (Sahu et al. 2020). Its emissions have provided critical insights into blazar jet dynamics and high-energy astrophysical processes.

2. Methodology

To model the SED of Mrk 421 and Mrk 501 we assumed a one-zone radiation modeling approach. The model assumes that non-thermal relativistic particle populations exist in a spherical emission region in the relativistic jet. This region is defined by its radius, R, magnetic field strength, B, and the bulk Lorentz factor, Γ. Particle populations are distributed as a simple power

[1] https://www.hawc-observatory.org/
[2] https://veritas.sao.arizona.edu/

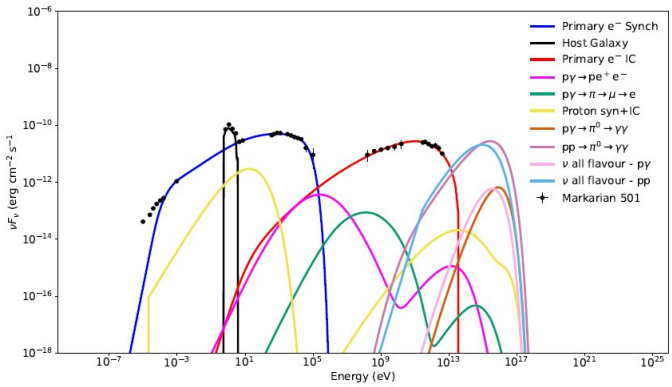

Figure 1. SED modelling of Markarian 421.

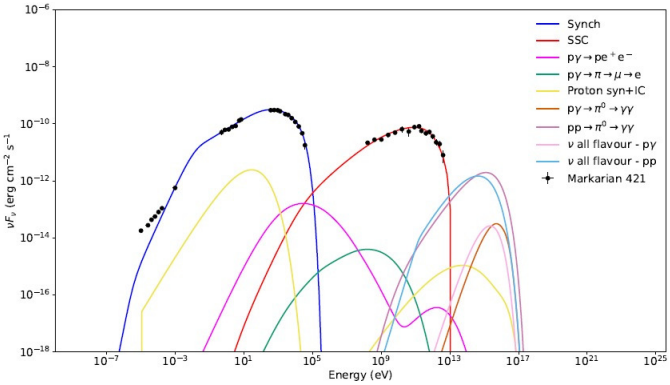

Figure 2. SED modelling of Markarian 501.

law $dN/d\gamma \propto \gamma^{-\alpha}$, where N is the number of particles, α is the spectral index and γ is the Lorentz factor. The jet is assumed to be observed at an angle $\theta_{obs} = 1/\Gamma$ relative to the jet axis, resulting in a Doppler factor $\delta_D \approx \Gamma$. For the SED leptonic origin we used the JetSeT[3] software (Tramacere 2020), which simulates radiative and accelerative processes in relativistic jets and adjusts numerical models to observational data. This is an open-source C/Python code that defines a dataset and links it to Astropy[4] tables and quantities. The physical processes include SSC (Synchrotron Self-Compton), external Compton (EC) scattering, and EC from cosmic microwave background radiation. This software can constrain the model during the pre-fit stage based on precise and previously published phenomenological trends (e.g., Rodrigues et al. 2024), using parameters such as spectral indices, fluxes, peak frequencies, and spectral curvatures. Moreover, for the SED lepto-hadronic modelling we used the AM3 (Astrophysical Multi-Messenger Modeling) software[5] (Klinger et al. 2024), which solves time-dependent partial differential equations for the energy spectra of electrons, positrons, protons, neutrons, photons, neutrinos, and secondary charged particles (pions and muons) embedded in an isotropic magnetic field.

3. Results and Discussion

Figures 1 and 2 show the SED of Markarians 421 and 501. The results indicate a purely leptonic origin for the multi-wavelength observation of both Markarians. The processes from the lepto-hadronic model are: proton-photon interactions (pγ) which are observed from 10^{12} eV to 10^{16} eV. Pion production from proton-proton interactions (pp $\rightarrow \pi^0$) is mainly seen from approximately 10^9 to 10^{17} eV, while proton-driven SSC processes are significant from 10^8 to 10^{16} eV. The all-flavor neutrino fluxes exhibit a peak near 10^{14} eV and extend to 10^{16} eV. However, the hadronic model for the blazars has no significant impact, indicating that the data are well explained solely by emission from accelerated electrons (synchrotron (blue curve) + inverse Compton scattering (red curve)).

4. Conclusion

The study carried out explored the potential of Markarians 421 and 501 as possible sources of astrophysical neutrinos, gamma rays, and cosmic rays. The work analyzed the interactions between high-energy protons and ambient photons within blazar jets to investigate neutrino production and gamma-ray emission from charged particles. The results have indicated that a purely leptonic model is sufficient to explain the high-energy gamma-ray emissions observed in both Markarians.

These analyses highlight the importance of multimessenger investigations in expanding our understanding of physical processes in extreme environments and underscore the critical role of continued development in observational experiments, contributing to the advancement of particle astrophysics.

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[3] https://jetset.readthedocs.io/en/1.3.0/index.html
[4] https://www.astropy.org/
[5] https://am3.readthedocs.io/en/latest/