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A tool to understand emission mechanisms of blazars through their high-energy gamma-ray emission

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The blazar SED is characterized by two energy components. Evidence suggests that the low-energy component is generated by the synchrotron mechanism, but for the high-energy component, the mechanism is still uncertain. Two main models have been proposed to explain this emission. According to the leptonic model, a correlation between the emission of both SED components would be expected, while the hadronic model would explain the highest gamma ray and neutrino emission. The particle acceleration processes inside the relativistic jets of AGNs remain another open question. This article presents a summary of some studies that leverage high-energy gamma-ray emissions to enhance our understanding of the particle acceleration and emission mechanisms of blazars.

KEYWORDS
blazars, hadronic model, HBL, HE and VHE gamma rays, leptonic model, Mrk 421

1 | INTRODUCTION

Blazars, classified as active galactic nuclei (AGN), possess a relativistic jet that points directly at the observer, making them one of the most energetic extragalactic sources and the predominant population in the γ-ray sky (Abdo et al. 2009; Cerruti 2020). They exhibit emission across the entire electromagnetic spectrum, characterized by non-thermal radiation generated through energetic processes occurring in the relativistic jet. In the $\nu F \nu$ space representation, their spectral energy distribution (SED) features a distinctive two-humped shape, with the first hump spanning from radio to X-rays energies, and the second hump from MeV to TeV gamma-ray energies (Abdo et al. 2010; Donnarumma et al. 2009; Fossati et al. 1998).

Optical evidence suggests that the low-energy spectral "hump" is due to synchrotron radiation emitted by relativistic electrons within the jet (Cerruti 2020; Fraija et al. 2017; Tavecchio et al. 2010). The energy peak of this hump is often referred to as the synchrotron peak. The frequency at which this peak is $\left(\nu^s_{peak}\right)$ has been used to classify blazars into three different groups: The low-synchrotron-peaked blazars (LSP) if $\nu^s_{peak} < 10^{14}$Hz, the intermediate-synchrotron peaked blazars (ISP) if 10^{14}Hz $< \nu^s_{peak} < 10^{15}$ Hz, and the high-synchrotron-peaked blazars (HSP) if $\nu^s_{peak} > 10^{15}$ Hz (Ackermann et al. 2015).

To account for the spectral high-energy "hump", various models have been proposed with the most widely accepted being the "leptonic model". These models proposed that relativistic electrons scatter low-energy photons through inverse Compton (IC) to produce high-energy photons. One such model is the single-zone synchrotron self-Compton (SSC) model, which proposes that IC emission is produced by the same population of relativistic electrons that generates the synchrotron emission. Consequently, one would expect to observe a correlation between low- and high-energy emissions as some authors have reported (González et al. 2019). However, when the model does not fit the observations, other models have to be taken into consideration, such as the "hadronic model". The gamma-ray energy emission can be mainly produced by Photo-Meson production and the Bethe–Heitler pair production, although also proton–proton interactions can also occur (Cerruti 2020). The importance of the hadronic models is the production of high-energy neutrinos for the photon–meson cascades.

Blazars are also reported as variable sources, with changes in their luminosity at different time scales that range from minutes to years (Aharonian et al. 2007; MAGIC Collaboration et al. 2008; Paliya et al. 2015). Learning about the physics that produces the variability is important to the understanding of the emission and acceleration mechanisms in blazars. Long-term monitoring campaigns from current and future experiments will contribute to this matter. Experiments such as the Fermi-LAT detect sources in the energy range of 20 MeV–300 GeV and constitute an excellent tool for blazar monitoring, and at higher energies, above 100 GeV, the Imaging Air Cherenkov Telescopes (IACTs) play important roles in the AGN studies. As for the studies of particle acceleration in the AGNs jets, it has been reported that the high-energy gamma-ray flux distribution can be described by the sum of a Gaussian and a lognormal distribution (Sacahui et al. 2021; Tluczykont et al. 2010). The lognormal distribution can be indicative of the presence of multiplicative acceleration processes such as a cascade process (Uttley et al. 2005), while the normal distribution, interpreted as a baseline flux, can be attributed to additive processes.

This article presents a summary of some studies that leverage high-energy gamma-ray emissions to enhance our understanding of the emission mechanisms of blazars. Section 2 summarizes the results of a work that investigates the one-zone synchrotron self-Compton (SSC) model to evaluate how varying parameter conditions impact correlations between X- and high-energy γ-ray emissions. Section 3 features a multi-frequency study to identify the energy regimes that exhibit correlations for the blazar Mrk 421. In Section 4 a study to examine whether the X- and γ-ray correlation in other high-peaked blazars (HBL) aside from Mrk 421 is presented. Lastly, an analysis of the distribution of high-energy γ-rays is presented in Section 5 as a tool to understand the nature of particle acceleration mechanisms.

2 | THE X- AND γ-RAY CORRELATION WITHIN THE ONE-ZONE SYNCHROTRON SELF-COMPTON MODEL

HBL, or high-frequency-peaked BL Lac objects, are a specific type of blazar that are capable of emitting gamma rays with energies up to TeVs, making them excellent candidates for studying the mechanisms of high-energy emission. According to the synchrotron Self-Compton leptonic model, a multi-wavelength correlation is expected. In particular, it is possible to study the correlation between the spectra energy distribution (SED) energy peaks of both components, namely X-rays and gamma-rays. For instance, in the study of González et al. (2019), a 14-year correlation between X-rays and TeV gamma rays of the HBL blazar Markarian 421 (Mrk 421) was studied, finding that the correlation could be modeled with a linear function and was valid at both low and high states. This result is consistent with the predictions of the SSC leptonic model with a unique magnetic field value for the emission region. However, at the highest gamma-ray fluxes observed, the correlation was no longer valid in any of the timescales studied.

In Aguilar (2021), we tested previous results for a Mrk 421-like source, assuming different parameter assumptions. The jet was modeled within a one-zone SSC model using four physical parameters: the Lorentz factor, the size of the emission region (taken to be spherical), the electron density (N_e), and the magnetic field intensity (B) while assuming a constant electron spectral index. It studied how different parameter assumptions, B vs. N_e, changed the shape of the correlation, in particular its slope. It was found that the steeper the correlation, the narrower the parameter space that reproduces the expected fluxes. Additionally, it was found that the flares were possible when the electron density was increased while the magnetic field value had to decrease for the highest flares.

For future studies, a better characterization of the parameter space behavior is needed. This could be achieved by adding temporal spectral evolution to the model, particularly for the highest activities. Additionally, it is essential to consider the observed harder-when-brighter evolution of the flux of the given source of study as input. Furthermore, the study was limited to the use of power laws as a description of electron distribution, which could have effects on the accurate description of the X-ray emission at some times. With an improved model, it will be possible to study a sample of blazars, understand the behavior of the physical parameters of each source, and determine whether these parameters behave similarly and can be grouped into a general behavior or are different for each blazar.

3 | MULTI-FREQUENCY STUDY OF MRK 421 TO LOOK FOR EMISSION CORRELATIONS

As mentioned before, González et al. (2019) found a unique, general, strong, and linear correlation between

X-rays and TeV gamma rays for the HBL blazar Mrk 421 in a long-term study independently of the timescale. This result raises the question of whether there exists a long-term correlation between other wavelengths and if so how it behaves. Usually, correlations are searched between analogous regions of the SED components in blazars. For example, between the peak fluxes of the components, i.e., for HBL blazars, between X-rays and VHE gamma rays, or before the peaks, between optical and HE gamma rays. For Mrk 421, the correlations obtained from previous studies to González et al. (2019) range from being only correlation indications (Donnarumma et al. 2008) to a statistical significance of $\sim 3\sigma$ (Cohen et al. 2014). And the strongest correlations found were between the optical band and HE gamma rays (Carnerero et al. 2017; Cohen et al. 2014) and a somewhat strong relation between radio at GHz and HE gamma rays (Lico et al. 2014; Max-Moerbeck et al. 2014).

The study that we presented in Castellanos (2022) searches for a correlation between the bands of radio at 37 GHz, optical at the R band, and gamma rays between 2 and 300 GeV of energy. The data for each band span more than 12 years from August 8, 2008 to May 2, 2021. The radio data were obtained from the radiotelescope Metsähovi located in Kirkkonummi, Finland, which is dedicated to the daily observation of Mrk 421. For the optical band, the data were obtained from two telescopes, one is the telescope Dall-Kirkham at the Tuorla Observatory in Piikkiö, Finland, and the other is the telescope KVA (Kungliga Vetenskap-Sakademien) located at the Roque de los Muchachos Observatory in La Palma, Spain. Both data sets were requested from the members of each monitoring program.[1] The gamma rays data were obtained from the Fermi Large Area Telescope (LAT, Atwood et al. 2009) instrument on board The Fermi Gamma-ray Space Telescope. This instrument observes gamma rays in the energy range from 20 MeV to $\gtrsim$300 GeV. The data files were obtained from the official Fermi mission website. The data reduction was performed using the ScienceTools version v11r5p3, and the response function **P8R3_SOURCE_V3** within Enrico,[2] a community-developed Python package to simplify Fermi-LAT analysis Sanchez & Deil (2013). The diffuse Galactic and isotropic components were modeled with the files **gll_iem_v07.fits** and **P8R3_SOURCE_V3.txt**, respectively. Events between 2 and 300 GeV were used, selected with a region of interest (ROI) of 15°, in addition, to a zenith angle of 100° to avoid contamination from the Earth. We performed the binned likelihood analysis in time intervals of 1 week to obtain the light curves in the energy range mentioned before. The fluxes were calculated using a power-law function with a spectral index of 1.8 to describe the spectral shape of Mrk 421 reported in the 3FGL. The data for the three energy bands were weekly binned to increase the statistics in the gamma data to be able to determine the spectrum. All the instruments used are part of Blazar Monitoring Programs.

The correlations obtained were best modeled with a linear function, $F_\eta = aF_\lambda + b$, where a and b are the parameters determined, and F_η and F_λ the measured fluxes at different energy bands, obtained with the D'Agostini Bayesian fit method D'Agostini (2005). This method takes into account an additional source of uncertainty, represented as σ_S, in addition to the measurement uncertainties of F_η and F_λ. This extra scattering of the data is not explicitly stated, and for simplicity, it is assumed to follow a normal distribution. We define the correlation range to include 99.7% of the data within $3\sigma_S$ and those points outside this range are not considered to belong to the correlation. Such outliers should be explained by other physical phenomena.

As a result, we found that there is a correlation between other energy bands for Mrk 421 aside X- and high-energy (VHE) γ-rays. These correlations, when exist, exhibit a linear behavior, similar to the study conducted by González et al. (2019). We found a correlation between the optical and HE gamma-ray bands, with a Pearson coefficient of $R^2 = 0.57$. Although, several outliers are observed for the highest high-energy γ-ray fluxes. The correlation between the radio and gamma-ray bands was inconclusive. Lastly, the radio and optical bands showed a positive correlation with a coefficient of $R^2 = 0.56$ and without outliers. The positive correlations between certain energy bands support the leptonic model, while the inconclusive result suggests that emissions in those energy bands might be created in different emission regions or by different uncorrelated mechanisms. The observed correlation between the optical and radio emissions could indicate that both are generated by the same emission mechanism. Another significant result is observed in the correlation between gamma rays and optical emissions, with the presence of outliers at the highest fluxes of HE gamma rays. Similar to the result reported in González et al. (2019) for gamma rays at TeV energies, which indicates that there might be a contribution at the highest energies from a different mechanism that remains uncertain.

4 | X- AND γ-RAY CORRELATIONS IN HBL BLAZARS

As stated above, in blazars, within the SSC model, we expect a correlation between the fluxes from both of the

[1] For the Metsähovi data: https://www.aalto.fi/en/metsahovi-radio-observatory/active-galaxies. For the optical data: https://users.utu.fi/kani/1m/.

[2] Enrico software: https://github.com/gammapy/enrico/.

SED components. In principle, these correlations can vary morphologically depending on, for example, the energy regime where the emission was created, the existence of multi-emission regions, the energy range, or the timescale of observation.

There are two energy regimes to consider when studying the emission of high-energy photons observed in blazars, since the nature of the flux correlations with other frequencies in these regimes may differ. The Thompson energy regime occurs when the energy of the photon is lower than the rest mass energy of the particle with which it interacts, i.e., $E_{ph} < E_{o,e}$. Here, because the flux depends on particle density and the synchrotron number of photons, the expected correlation is quadratic (Amenomori et al. 2003). On the other hand, when $E_{ph} > E_{o,e}$, we are into the Klein–Nishina (K–N) energy regime. In this regime, the cross-section of the interaction decreases and the resultant photons of the interactions have larger energy than in the Thompson regime. However, because of the fewer number of interactions, the correlation is expected to be linear (Katarzyński & Walczewska 2010). Another factor proposed by Katarzyński & Walczewska (2010) that changes the correlation shape is the jet composition by different emission regions. The value of the correlation indexes (linear, quadratic, cubic, etc.) results from the correlation indexes of each emission region. Lastly, the correlation may be different depending on the timescale of their variability. As blazars can have variability as rapid as minutes, a daily or monthly correlation will overshadow the smaller variability in different degrees, resulting in different correlations (Katarzyński et al. 2005).

With the results found in González et al. (2019), questions arise regarding whether all HBL blazars exhibit a unique or general correlation. If so, it would be interesting to determine whether information on the number of emission regions, magnetic field strength, or acceleration regime can be inferred from the correlation. In the master thesis by Osorio (2021), we found a sample of HBL blazars that were chosen with the following conditions: (1) an observed emissions >200 GeV; (2) a spectral index $\alpha > 2$; (3) a redshift <0.15 to avoid a great absorption due to EBL; and (4) simultaneous observations between soft X-rays and TeV gamma rays. There were four selected blazars, Markarian 501, 1ES 1969 + 650, PKS 2155 − 304, and 1ES 2344 + 514. Each of the four selected HBL blazars had different observation times, and the data used for the analysis came from 6, 5, 5, and 1 different observation campaigns for Mrk 501, 1ES 1959 + 650, PKS 2155 − 304, and 1ES 2344 + 514, respectively.

The preliminary results showed that the sources from which we had more data presented outliers in the correlation at the highest gamma-ray fluxes, similar to what was observed in Mrk 421. This suggests that the production of the highest fluxes in gamma rays in HBL blazars may not be solely due to leptonic mechanism, but rather a combination of radiative mechanisms. In addition, there was a disagreement with the theoretical expectations for the K–N energy regime, and what was expected to be observed in blazars with multiple emission zones as Mrk 421 (Carnerero et al. 2017). These results provide new insights into the physical characteristics of the emission zones in blazars.

In the future, we plan to expand our sample of sources to include IBL blazars and perform similar analyses. Additionally, we aim to quantify the contribution of the leptonic and hadronic components to the blazar's emission and investigate how these components contribute across different types of blazars.

5 | PHOTON FLUX DISTRIBUTION STUDIES

There are still several open questions in the study of AGNs, including the particle acceleration processes and the emission processes that occur in the relativistic jet in the very high energy (VHE) range. Blazars are an ideal laboratory for studying relativistic jets of supermassive black holes due to their flux variability. One way to characterize the particle acceleration mechanisms in blazars is by analyzing the flux distribution. A flux distribution exhibiting Gaussian or "normal" behavior is attributed to components that add up to produce the observed emission. On the other hand, a lognormal behavior is attributed to multiplicative or cascade processes (Uttley et al. 2005).

Previous studies have found that the flux distribution in the light curves of AGNs exhibits a behavior that differs from a Gaussian distribution, as it shows more pronounced tails at high fluxes. Uttley et al. (2005) observed a lognormal flux distribution in X-rays in both the black hole binary Cyg X-1 and the Seyfert 1 galaxy NGC 4051. Moreover, the same behavior was found in the blazar BL Lacertae by Giebels & Degrange (2009). This behavior is generally explained by fluctuations in the Shakura–Sunyaev accretion disk model (Shakura & Sunyaev 1976); however, this model cannot be applied to gamma-ray fluxes since fluctuations in the accretion disk cannot generate the relativistic Doppler boosting needed to justify timescale variability of minutes (Romoli et al. 2018).

In Rangel (2022), we carried out a study on the distribution of the flux of the BL Lac Markarian 421 source, in three spectral regions with observations spanning over 13 years: radio (37 GHz), visible (R filter), and gamma rays. The data for the radio and visible bands were the same as the data used by Castellanos (2022). The data of gamma-ray fluxes correspond to the period of almost 13

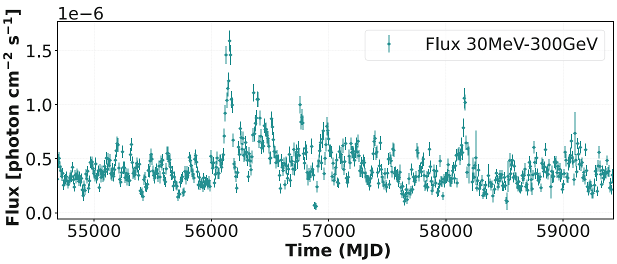

FIGURE 1 Light curve in gamma rays in the energy range of 30 MeV–300 GeV generated with Enrico package.

years from August 2008 to May 2021. They were obtained by the Fermi-LAT observatory. The light curves were generated as described in section 3, with a couple of different parameter values. The events were selected between 30 MeV and 300 GeV of energy, with a region of interest (ROI) of 10°, and a zenith angle of 90°. The binned likelihood analysis in time intervals of 1 week was used (Figure 1).

To conduct a flux distribution analysis in the three energy bands—radio, visible, and gamma ray—we first selected models to fit our sample using the Bayesian information criterion (BIC). Based on the criterion's results, we identified two models that best fit our sample, namely the Gaussian and lognormal functions. These functions are described by:

$$f(x;\mu,\sigma) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \quad (1)$$

and

$$f(x;\mu_{log},\sigma_{log}) = \frac{1}{x\sigma_{log}\sqrt{2\pi}} exp\left(-\frac{(log(x)-\mu_{log})^2}{2\sigma_{log}^2}\right). \quad (2)$$

The parameters of the Gaussian function are σ and μ, which represent the standard deviation and mean, respectively. On the other hand, for the lognormal function, the parameters are σ_{log} and μ_{log}. To obtain parameter values for both distribution functions based on our data, we used the maximum likelihood method. We then employed the Kolmogorov–Smirnov (KS) test as a statistical measure to assess the goodness of fit. The results are shown in Table 1 for the lognormal function fit. In the Figures 2–4, histograms with the two fitted functions are shown. The results show that for the three energy ranges, the behavior of the flux distribution is far from a normal distribution, as it has heavy tails at high fluxes, and resembles a lognormal function. Furthermore, the KS test for the three energy ranges indicates that the null hypothesis is rejected for the normal function, but not for the lognormal function. We notice that the parameters for σ_{log} for optical and gamma rays are the same, but not for the radio band.

TABLE 1 Lognormal function parameters for the three energy ranges.

Range	μ_{log}	σ_{log}
Radio	-0.66 ± 0.01	0.26 ± 0.01
Visible	-3.95 ± 0.01	0.41 ± 0.01
Gamma rays	-14.77 ± 0.01	0.41 ± 0.01

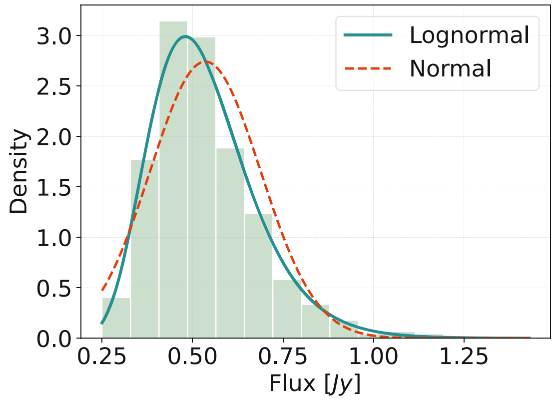

FIGURE 2 Histogram and probability density function of normal and lognormal distributions fitted to radio 37 GHz data.

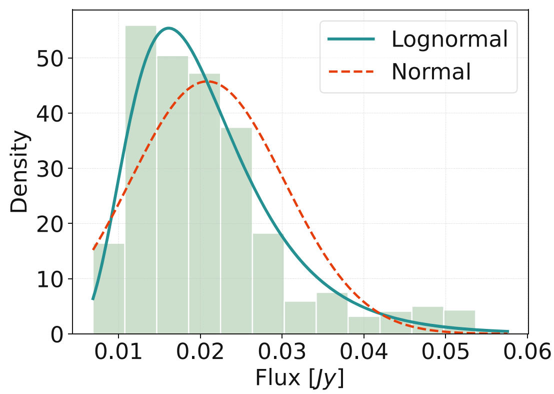

FIGURE 3 Histogram and probability density function of normal and lognormal distributions fitted to visible *R* filter data.

These results strengthen the evidence that not only optical and gamma-ray emissions arise from the same region but also from the same particle acceleration mechanism. However, deeper interpretations are needed.

6 | CONCLUSIONS

We have presented diverse studies to understand the emission and particle acceleration mechanisms in jets of blazars. These studies are mainly based on describing correlations between emissions at different wavelengths as well as flux distributions of such emissions. We have found several pieces of evidence that suggest that optical and

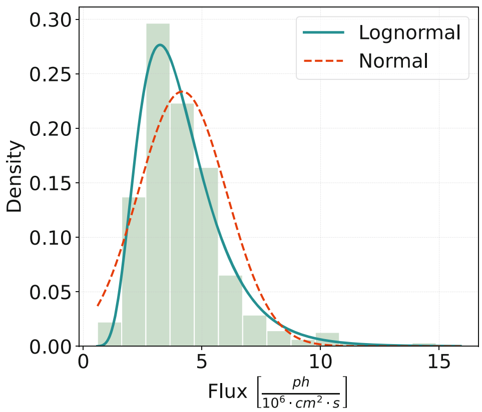

FIGURE 4 Histogram and probability density function of normal and lognormal distributions fitted to gamma rays data.

gamma-ray emissions are generated by correlated mechanisms, such as the SSC, and the particle acceleration mechanisms involved are of a multiplicative nature. Further studies are needed with data from longer periods of time. Efforts as the M@TE project are aimed at achieving this goal (Cuzco et al. 2023).

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