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Correlation between emission line luminosity and gamma-ray dominance in the blazar 3C 279

A. Dmytriiev,[a,*] **M. Böttcher**[a] **and T.O. Machipi**[a]

[a] *Centre for Space Research, North-West University*
Potchefstroom 2520, South Africa

E-mail: anton.dmytriiev@nwu.ac.za

The nature of blazar γ-ray emission still remains uncertain, in particular whether it is of a leptonic or hadronic origin. Here, we are testing the leptonic scenario for the Flat Spectrum Radio Quasar (FSRQ) 3C 279, with the inverse Compton (IC) scattering of external photons from the Broad Line Region (BLR) as the γ-ray production mechanism (IC-BLR scenario). Using a 10-year data set of the optical spectroscopy data from the Steward Observatory blazar monitoring program and Fermi-LAT γ-ray data, we search for a correlation between the Compton dominance and the emission line luminosity using the discrete correlation function (DCF) analysis. We find no significant correlation between these quantities at any time lag. However, the emission line luminosity moderately correlates with γ-ray flux at zero time lag. Additionally, we observe a strong correlation between the optical synchrotron continuum flux and γ-ray flux. These results support the interpretation within the leptonic IC-BLR scenario, where changes in the magnetic field and/or the bulk Lorentz factor drive the variations in Compton dominance rather than changes in the emission line luminosity.

38th International Cosmic Ray Conference (ICRC2023)
26 July - 3 August, 2023
Nagoya, Japan

*Speaker

PoS(ICRC2023)654

1. Introduction

Blazars, a type of radio-loud Active Galactic Nuclei (AGN), are characterized by relativistic jets pointed very closely towards the Earth's direction. Blazars are divided into BL Lac objects and Flat Spectrum Radio Quasars (FSRQs), with FSRQs being more luminous and possessing dominant electromagnetic power output in the γ-ray regime. The origin of the γ-ray emission from blazars and the exact location of the γ-ray production site in the jet remains unclear. Two competing scenarios, leptonic and hadronic, are invoked to explain the nature of blazar γ-ray emission. One of the most extensively studied FSRQs, 3C 279, has provided numerous valuable insights into the blazar emission processes. This object exhibits violent variability across a wide range of wavelengths (e.g. [1, 2]). Continuous observations of 3C 279 by the *Fermi* Gamma-ray Space Telescope since 2008 have revealed its dramatic flux variations in the γ-ray band, including rapid flares over time-scales as short as a few hours or even minutes [2, 3]. A great number of different studies have been conducted to understand the origin of the γ-ray emission from 3C 279 and the physical processes causing its variability. Diverse multi-band data sets obtained during different activity phases have been modeled using leptonic, hadronic, and lepto-hadronic models [4–6]. Based on multiple analyses of *Fermi*-LAT γ-ray data, studies [4, 7] support a leptonic scenario, in which the γ-ray emission originates from the inverse Compton (IC) scattering primarily of photons from the broad line region (BLR), potentially with some contribution from dusty torus photons, suggesting a close proximity of the emission region to the BLR. Conversely, hadronic models incorporating photo-hadron interactions have also been proposed, providing satisfactory results in explaining the very high energy (VHE) γ-ray emission observed by MAGIC in 2006 [5]. Furthermore, in attempts to distinguish among different emission scenarios, various studies have examined correlations between different spectral bands, in particular, between flux variations in the optical and γ-ray regimes [1, 8], yet the results have yielded controversy and remain inconclusive.

In this study, we focus on testing the leptonic scenario for γ-ray emission production, specifically exploring the hypothesis that the GeV emission from 3C 279 arises from IC upscattering of soft photons from the BLR by high-energy electrons residing in a compact region of the jet, referred to as a "blob" ("IC-BLR" scenario). We aim to examine the correlation between the luminosity of emission lines originating in the BLR and the Compton dominance (CD) parameter, expected in the IC-BLR scenario. The CD is defined as the ratio between the IC and synchrotron SED fluxes, $CD = F_{\mathrm{IC}}/F_{\mathrm{syn}}$. This parameter is proportional to the energy density of the target photon field in the AGN rest frame U_{rad}: $CD \propto (N_e U'_{\mathrm{rad}})/(N_e U'_{\mathrm{syn}}) \propto U_{\mathrm{rad}}\Gamma^2/B^2$, and in turn U_{rad} is proportional to the flux of the emission lines as observed by a distant observer. In contrast to previous correlation studies, our investigation uniquely focuses on the Compton dominance rather than only the γ-ray flux, allowing us to assess not only the validity of the leptonic scenario for 3C 279, but also to specifically verify the IC-BLR hypothesis.

2. Data

Our analysis necessitates knowledge of three fundamental quantities: emission line flux, synchrotron flux, and gamma-ray flux, all measured as a function of time. We determine the optical emission line flux and synchrotron continuum flux depending on time using optical spectroscopy

PoS(ICRC2023)654

data from the Steward Observatory blazar monitoring program[1]. We use the data of *Fermi*-LAT to extract the long-term γ-ray light curve of the source. To assess the Compton dominance, we calculate the ratio between the γ-ray energy flux in the range 0.1 – 100 GeV, and the optical synchrotron λF_λ flux measured at 6000 Å. This wavelength is chosen to avoid contamination from thermal emission of the accretion disk.

2.1 Optical data

The Steward Observatory of the University of Arizona conducted a 10-year monitoring program (2008 – 2018) for a subset of *Fermi*-LAT blazars in the optical band. We use optical spectra of 3C 279 from this program to measure the emission line luminosity and synchrotron continuum flux as a function of time. We select properly scaled spectra with consistent normalization based on V-band magnitudes obtained through differential spectrophotometry. The resulting data set consists of 504 spectra covering the wavelength range of 4000 – 7550 Å, measured between November 24, 2008, and July 7, 2018 (at irregular time intervals). The spectra exhibit a power-law-like continuum, with notable features at blue wavelengths due to Galactic extinction or accretion disk contributions below 5000 Å. The most prominent emission line observed is Mg II (λ = 2798 Å in the source's frame, redshifted to λ = 4298 Å in the observer's frame), while other emission lines are relatively weaker and not considered in our analysis.

We employ the Python module LMFIT to fit each optical spectrum and derive relevant model parameters. The synchrotron continuum level is determined by fitting a power law function to the optical spectra within the wavelength range of 5000 – 6500 Å, excluding possible contamination from the accretion disk and the strong O_2 absorption line at 6980 Å. The synchrotron continuum flux, $F_{\rm syn}$, is obtained by evaluating λF_λ at the wavelength of 6000 Å from the best-fit model. We also calculate the uncertainty of $F_{\rm syn}$ using the uncertainties in the best-fit continuum normalization and spectral index. To measure the flux of the Mg II emission line, we fit the spectra within a narrow wavelength range of 4150 – 5000 Å using a combination of a power law and a Gaussian model. This approach allows us to extract the emission line flux above the local continuum, minimizing potential biases that might arise when performing a global spectral fit. For each individual spectrum, we first identify the Mg II emission line visually, requiring its clear visibility above continuum variations. In certain spectra where significant noise is present in the wavelength range around the emission line, the large continuum variations can considerably contaminate or suppress the emission line, rendering it impossible to measure reliably. Additionally, we exclude spectra in which the emission line width falls outside the range of 21 – 130 Å, which corresponds to the typical velocities of BLR clouds. Out of the initial 504 spectra, 169 meet these criteria, providing reliable measurements of the Mg II emission line flux. At the same time, the synchrotron continuum flux $F_{\rm syn}$ is measured for all 504 optical spectra. Fig. 1 displays the obtained synchrotron continuum flux (first panel) and Mg II emission line flux (second panel) as functions of time over the 10-year period (2008-2018).

2.2 *Fermi*-LAT γ-ray data

We analyze 10 years (2008 – 2018) of *Fermi*-LAT data of 3C 279 using the *Fermipy* package (fermipy version 1.0.1, ScienceTools version 2.0.8). We select events from Nov 1, 2008, to Jul

[1] http://james.as.arizona.edu/~psmith/Fermi/DATA/Objects/3c279.html

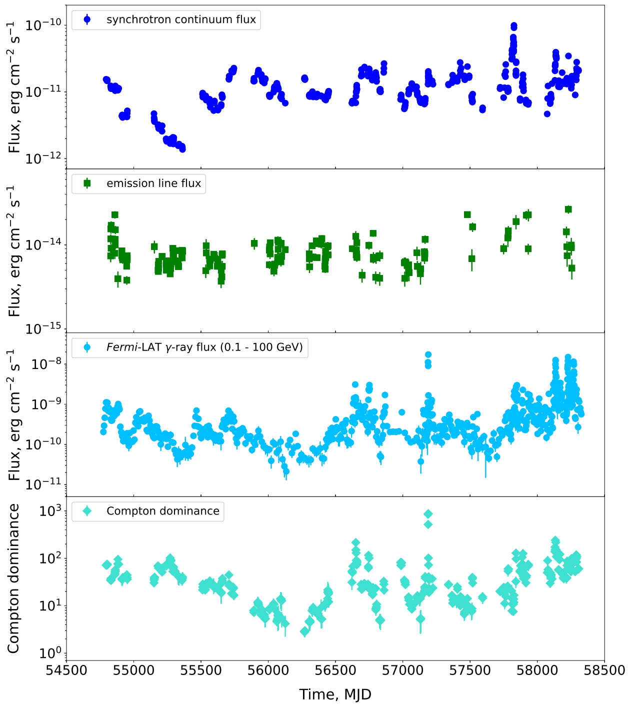

Figure 1: Long-term (2008–2018) light curves depicting four observational quantities of 3C 279. Panel 1: optical synchrotron continuum flux λF_λ at $\lambda = 6000$ Å (full sample of 504 spectra). Panel 2: Mg II emission line flux (sub-sample of 169 spectra). Panel 3: *Fermi*-LAT γ-ray energy flux in the 0.1 – 100 GeV range. Panel 4: Compton Dominance.

31, 2018, within a 15° ROI centered on the source. We choose events of the "SOURCE" class (`evclass=128`) with FRONT+BACK converting events (`evtype=3`). We apply a zenith angle cut of $z < 90°$. The analysis includes the Galactic diffuse background modeled with the *gll_iem_v07* template and the isotropic diffuse background using the *iso_P8R3_SOURCE_V3_v1* template. We use the `P8R3_SOURCE_V3` instrument response functions (IRFs) in our analysis. Point sources within the ROI are added to the model from the 4FGL catalog. We optimize the model by removing point sources with low significance (TS < 9) and low predicted counts ($n_{\text{pred}} < 3$). For the remaining point sources, normalizations of those with TS > 10 and those within 3° of the ROI center are freed. Also, we free the normalizations of 3C 279 and of the background components. We then calculate the light curve of 3C 279 (energy flux versus time) using an adaptive time binning approach, with finer bins for high-flux states and wider bins for low-flux states. The resulting 10-yr *Fermi*-LAT light curve in the energy range 0.1 – 100 GeV is presented in Fig. 1 (third panel).

3. Correlation analysis

3.1 Computation of Compton dominance

We compute the Compton dominance, which is defined as the ratio of the peak νF_ν flux of the inverse Compton (IC) emission to that of the synchrotron emission. The γ-ray light curve serves as a measure of the IC νF_ν flux, while the computed optical synchrotron λF_λ flux at 6000 Å

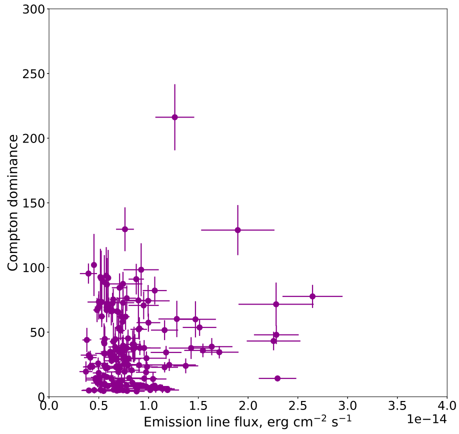

Figure 2: Scatter plot showing the relationship between Compton dominance and Mg II emission line flux for simultaneous measurements. Both axes are displayed in a linear scale to aid in identifying a potential linear correlation.

approximates the synchrotron νF_ν flux. We bin the CD using the time intervals of the synchrotron light curve, for each data point of which we determine the corresponding γ-ray flux from the *Fermi*-LAT light curve, and evaluate the ratio of the γ-ray to synchrotron fluxes, obtaining the CD value in each time bin. The resulting CD light curve is presented in Fig. 1 (fourth panel).

3.2 Correlation analysis for simultaneous measurements

To examine a potential correlation between the emission line luminosity and the CD, we create a scatter plot of simultaneous measurements of the emission line flux and CD (Fig. 2). The plot reveals a lack of significant correlation between the two variables. Consequently, we investigate the possibility of a correlation between the variables with a time lag between them.

3.3 Discrete correlation function analysis

We perform the discrete correlation function (DCF) analysis [9] to explore correlation between emission lines and γ-ray dominance with a time lag, which, if observed, could be interpreted within the IC-BLR scenario as a manifestation of light travel effects within the source. To unravel the intricate relationships between various observational quantities, we employ the DCF analysis to explore correlations among four pairs of quantities: (1) emission line flux vs. Compton dominance, (2) synchrotron continuum vs. γ-ray flux, (3) emission line vs. γ-ray flux, and (4) synchrotron continuum vs. emission line flux. The DCF is calculated within a time lag range of -100 d $\leq \Delta t \leq$ 100 d, using different time bin values (5, 7, 10, and 14 days). We evaluate the significance of observed correlations through Monte Carlo simulations. For each pair of quantities, we perform 30 000 runs where the light curve of one quantity is randomly shuffled and the DCF is computed. The resulting stacked DCFs yield 90%, 95%, and 99.7% probability contour lines, with a 14-day time lag binning chosen for optimal results. The resulting DCFs are presented in Fig. 3. We find no significant correlation between emission line flux and Compton dominance, while the optical synchrotron continuum shows a strong correlation with γ-ray flux near zero time lag, as well as a statistically significant second peak in the relevant DCF at a ~90 d time lag. Additionally, a modest

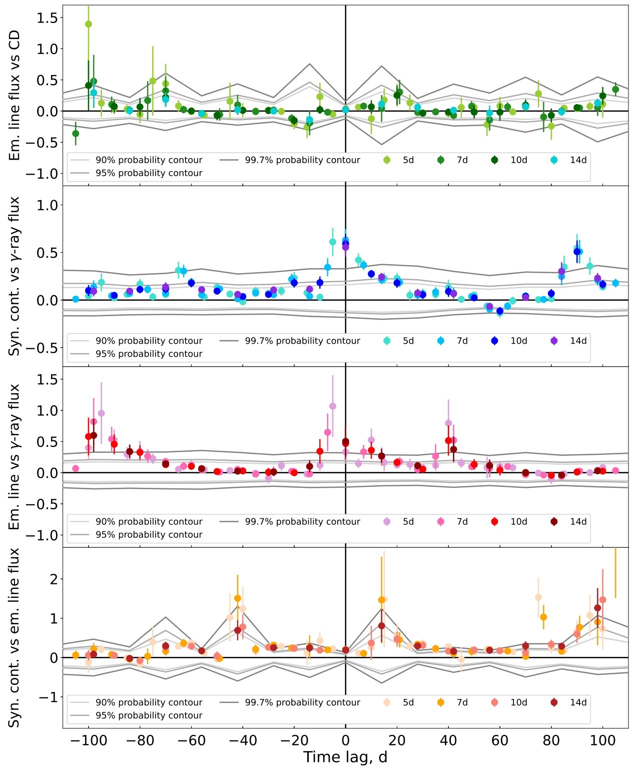

Figure 3: DCF as a function of time lag for four pairs of quantities analyzed. Panel 1: emission line flux versus Compton dominance. Panel 2: optical synchrotron continuum versus γ-ray flux. Panel 3: emission line flux versus γ-ray flux. Panel 4: optical synchrotron continuum versus the emission line flux. Different colors indicate distinct time lag binnings (5, 7, 10, and 14 days), and the gray contours represent the 90%, 95%, and 99.7% (3σ) probability contours in progressively darker shades.

correlation between emission line luminosity and γ-ray flux is observed at zero time lag. The optical synchrotron continuum flux and emission line flux do not exhibit substantial correlation.

4. Discussion

The strong correlation ($\approx 0.6 \pm 0.1$) between the optical continuum and γ-ray flux at zero time lag supports their co-spatial origin, favoring the leptonic scenario. However, the nature of the second peak in the DCF (0.5 ± 0.1) with a time lag of $\sim$90 d is not immediately obvious. Assuming a Doppler factor of $\delta \sim \Gamma \sim 10$, the 90-d lag corresponds to a travel distance of $\sim$7.5 pc. Considering the evidence of γ-ray production in blazars at multi-parsec distances away from the central black hole (e.g. [10, 11]), a possible explanation is that the emitting region, represented by a moving plasma "blob", traverses two shocks with a separation of approximately 7 – 8 pc. The first shock, situated closer to the central engine, gives rise to simultaneous optical and γ-ray flares. As the blob reaches the second shock, re-accelerated electrons interact with infrared photons from the dusty torus via the IC process, producing γ-ray emission. Due to the presumed very low magnetic field in the jet at large distances from the central engine, synchrotron emission is expected to be negligible. Consequently, the flares at the second shock become Compton-dominated, resulting in a γ-ray "echo" following the first flare with a time delay of ~90 d.

Then, the synchrotron continuum exhibits no correlation with the emission line flux, indicating that the variability in the synchrotron emission of the jet has no direct influence on the production of emission lines in the BLR. This suggests that the emission line luminosity variations primarily arise from the varying luminosity of the accretion disk emission, which is then reprocessed by the BLR.

Next, we find a moderate positive correlation (0.5 ± 0.25) between the emission line and γ-ray flux at or near zero time lag, which is marginally significant. However, no significant correlation is observed between the emission line flux and the Compton dominance variations. These findings can be interpreted in the following way. The slight correlation between the emission line luminosity and γ-ray flux at zero time lag can be naturally explained within the assumed IC-BLR scenario. The γ-ray luminosity L_γ, is proportional to the emission line luminosity, $L_{\rm eml}$, but also depends on other parameters such as electron number density $N_{\rm e}$, Γ, and δ: $L_\gamma \propto N_{\rm e} L_{\rm eml} \Gamma^2 \delta^4$. Therefore, the relative variations in $N_{\rm e}$ and $\Gamma^2 \delta^4$ are comparable to or weaker than those in the emission line luminosity. On the other hand, Compton dominance is $CD \propto L_{\rm eml} \Gamma^2 / B^2$, and thus the lack of a clear correlation between the emission line flux and the Compton dominance suggests that the dominant factors driving the variations in Compton dominance are likely the magnetic field and Lorentz factor changes, rather than the emission line luminosity. Considering the inferred comparable relative amplitudes of variability for emission line luminosity and $\Gamma^2 \delta^4$, it can be concluded that magnetic field changes have the strongest impact on the dramatic variations in Compton dominance.

Overall, this study highlights the challenge of disentangling the impact of specific parameters on each other. Previous studies (e.g. [8]) have also faced difficulties in understanding the optical-γ-ray correlations in 3C 279, with different scenarios proposed to explain the simultaneous variations in these fluxes depending on the activity state. Overall, the complex interplay of physical processes and the presence of degeneracies make it challenging to pinpoint the precise relationships between the observed quantities.

5. Conclusions

In this study, we conduct a comprehensive correlation analysis using a decade-long optical and γ-ray data set of 3C 279 to examine the origin of the γ-ray emission from the source and its long-term variability. As a result, we find a pronounced correlation between the optical synchrotron continuum flux and the GeV γ-ray flux at a zero time lag, indicating their co-spatial production and supporting a leptonic γ-ray emission origin. In addition, a moderate correlation at a ~90 d lag is seen between these quantities, suggesting a scenario where a plasma blob traveling along the jet crosses two shocks with a $\sim 7-8$ pc separation, with a Compton-dominated flare at the second shock. No substantial correlation is observed between the optical synchrotron continuum flux and the emission line luminosity, indicating that BLR emission line flux amplifications are mainly triggered by high states of the accretion disk rather than jet-related synchrotron flares. A moderate correlation is identified between the emission line luminosity and the γ-ray flux at zero time lag, supporting an IC-BLR origin of GeV γ-ray emission. The lack of a clear correlation between the emission line luminosity and the Compton dominance suggests that changes in the

Compton dominance are primarily driven by strong variations in magnetic field and/or bulk Lorentz factor, while the emission line luminosity variations play a minor role.

6. Acknowledgments

A.D. would like to acknowledge M. Zacharias and C. Boisson for fruitful discussions, which helped to greatly expand the coverage and depth of this study. The work of M.B. was supported by the South African Research Chairs Initiative of the National Research Foundation[2] and the Department of Science and Innovation of South Africa through SARChI grant no. 64789. Data from the Steward Observatory spectropolarimetric monitoring project were used. This program is supported by Fermi Guest Investigator grants NNX08AW56G, NNX09AU10G, NNX12AO93G, and NNX15AU81G.

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