PROCEEDINGS OF SCIENCE

Long-term multi-wavelength analysis of the FSRQ OP 313

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The Flat Spectrum Radio Quasar OP 313 is a high-redshift blazar that was characterized by intense γ-ray emission starting from November 2023 to March 2024, as observed by the Large Area Telescope (LAT) on board the *Fermi Gamma-ray Space Telescope* (*Fermi*). We present a multi-wavelength analysis covering 15 years of *Fermi*-LAT observations, from August 2008 to March 2024, to understand the mechanisms involved in particle acceleration inside the jet of this galaxy, and how emitted radiation in different wavelengths is connected. We analyzed a large sample of datasets coming from different facilities and projects to look at the trend in the multi-wavelength light-curves. From these, we identified the 7 most intense γ-ray flaring periods, and we analyzed each of them to unveil the responsible physical mechanisms. We realized for each of them the photon index versus flux plot in order to identify potential hysteresis patterns, and then, a kinematic study of the VLBA dataset was pursued to see if new knots arose in the jet before or during the 7 flaring periods we see. Finally, we performed an SED modeling for 2 of the 7 flaring periods. From the SED modeling, we found that a photon field coming from the dusty torus outside the jet is responsible for the γ-ray emission we saw starting from November 2023.

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1. Introduction

OP 313, also known as B2 1308+326, is a Flat Spectrum Radio Quasar (FSRQ) at a redshift of $z = 0.997$ [1] and coordinates RA = 197.619433 deg and Dec = 32.345495 deg [2]. *Fermi*-LAT detected an increase in flaring activity from OP 313 on the 22nd of November, 2023. The first peak of activity was reached on the 24th of November 2023 with an averaged γ-ray flux at energies larger than 100 MeV of $(1.8 \pm 0.2) \times 10^{-6}$ ph cm^{-2} s^{-1}, approximately 40 times larger than the value reported in the fourth *Fermi* Large Area Telescope (4FGL) Data Release 4 catalog [3]. Additionally, the photon index 1.80 ± 0.06 was significantly harder than the value reported in the 4FGL-DR4 reported value of 2.34 ± 0.02. This flare led the *Fermi* collaboration to publish the first ATel on the renewed activity of this source [4]. The high state of OP 313 was remarkably seen by the Large Sized Telescope-1 (LST-1) of the Cherenkov Telescope Array Observatory (CTAO) located at La Palma in December 2023 [5]. This quasar is the most distant quasar observed at Very-High-Energy so far. Another major flare from this source was seen on the 27th of February, 2024. The detected flux was the highest ever observed by LAT for OP 313: $(3.1 \pm 0.4) \times 10^{-6}$ phcm^{-2}s^{-1}, 60 times larger than the value reported in the 4FGL catalog, with photon index 1.81 ± 0.09. Another ATel was published by the LAT collaboration [6].

2. Multi-wavelength light-curves of OP 313

The light-curves from γ-ray to radio frequencies are shown in Figure 1. All of them show the emission of OP 313 from the beginning of the *Fermi* mission, on 4th of August 2008, to the 9th of March 2024 (MJD 54682.7 - 60378.0). The X-ray (b) and ultraviolet (c) datasets are from *Neil Gehrels Swift Observatory* (*Swift*)'s X-Ray Telescope (XRT) and Ultraviolet/Optical Telescope (UVOT) instruments. The optical light-curve (d) is obtained using datasets coming from different projects: CRTS, KAIT, Tuorla Observatory (Tuorla), ATLAS, and Palomar ZTF. In e) plot shows FERMI-GST AGN Multi-frequency Monitoring Alliance (F-GAMMA) data from 23.05 to 225 GHz, the Submillimeter Array (SMA) [1] data at 225, 273 and 350 GHz, including SMAPOL data at 225 GHz, Metsähovi Radio Observatory [2] the total density fluxes at 37 GHz, and the total density fluxes as well of the VLBA-BU-BLAZAR program at 43 GHz. In f) plot are presented the F-GAMMA [3] public data from 2.64 to 14.60 GHz as well as Monitoring Of Jets in Active galactic nuclei with VLBA Experiments (MOJAVE) public data total density fluxes at 15 GHz.

The trend of the light-curves in γ-rays, X-rays, ultraviolet, and optical shows an increasing activity flux starting from 2022. Before then, the source is characterized by small flares marginally visible in the γ-ray light-curve. Instead, looking at the radio light-curves, the source exhibits significant variability over 15 years. The common trend between all the different radio frequencies is that the source was characterized by high fluxes from the beginning of our analysis in 2008 and then it shows a decreasing trend until 2019, when it started to increase again.

[1] http://sma1.sma.hawaii.edu/

[2] https://www.aalto.fi/en/metsahovi-radio-observatory

[3] https://www3.mpifr-bonn.mpg.de/div/vlbi/fgamma/fgamma.html

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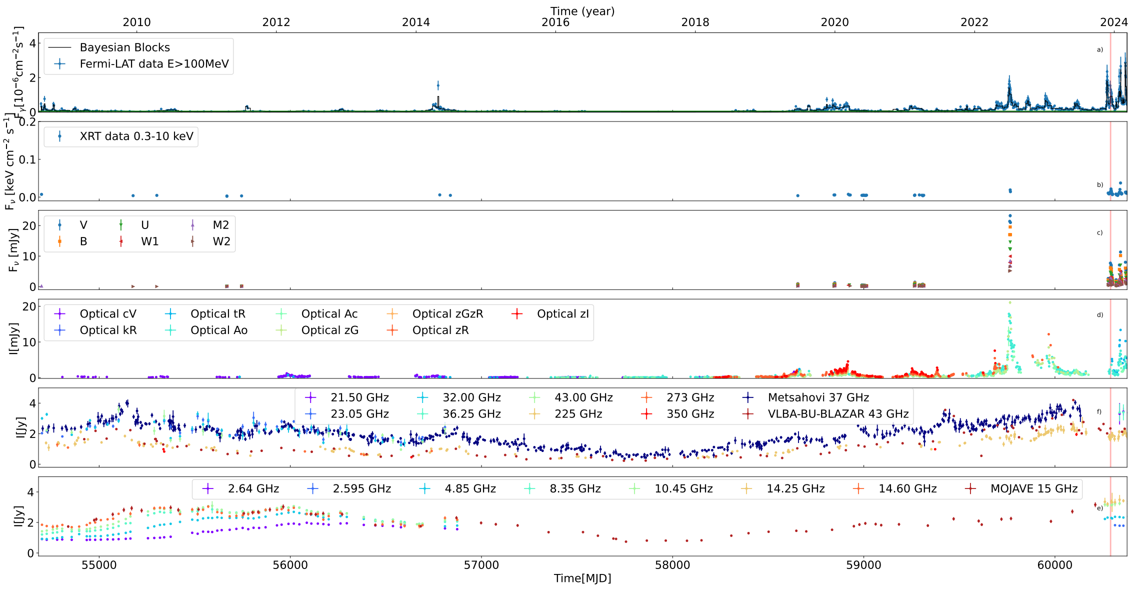


Figure 1: Multi-wavelength lightcurves of OP 313. The red vertical bands represent the period in which OP 313 was detected by LST-1 at La Palma. a: OP 313's LAT light-curve from August 4th, 2008, to March 9, 2024. b: *Swift*-XRT X-ray light-curve from 0.3 to 10 keV. c: *Swift*-UVOT light-curve. u, v and b optical *Swift*-UVOT filters are included. d: Optical light-curve from different datasets and filters. CRTS V-filter data are shown with the cV label, KAIT R-filter data are shown with the label kR, Tuorla R-filter data are shown with the label tR, ATLAS o and c-filters data are shown with the label Ao and Ac, and Palomar ZTF g, r, and i-filters data are shown with the label zG, zR, and zI. The label zGzR refers to observations in which both filters were used. e: Radio Single Dish F-GAMMA light-curves above 15 GHz, SMA data at 225 GHz , 273 and 353 and 350 GHz, including SMAPOL data at 225 GHz light-curves, Mets*ä*hovi at 37 GHz and VLBA-BU-BLAZAR at 43 GHz light-curves. f: Radio Single Dish F-GAMMA light-curves below 15 GHz and MOJAVE Very Long Baseline Array (VLBA) light-curve.

3. Selection of the flaring periods of interest

From Figure 1, we noticed that the source started to show consistently flaring activity at the end of 2021. Of particular interest is the flaring activity, from γ-ray to optical frequencies, which started in 2022 and continued until the last date of this study. Figure 2 shows the γ-ray and optical light-curves from the 1st of January 2022 to the 9th of March 2024. There is a visible good correlation between the two datasets, even if there is a lack of optical data in the flaring period reported in [4].

We identified the highest γ-ray flaring periods in this time window by looking at the Bayesian blocks that contained the highest average flux. We identified 7 different ones indicated with black dashed lines in Figure 2. The fourth and sixth flaring periods are not between the brightest but happened in the flaring periods reported by the LAT collaboration in the ATel [4] and [6]. Since we want to study the mechanisms responsible for this intense flaring activity, we decided to include them. In Figure 2, the first flaring period is more intense in the optical wavelengths than in the γ-ray, while the others are more intense in the γ-ray energies.

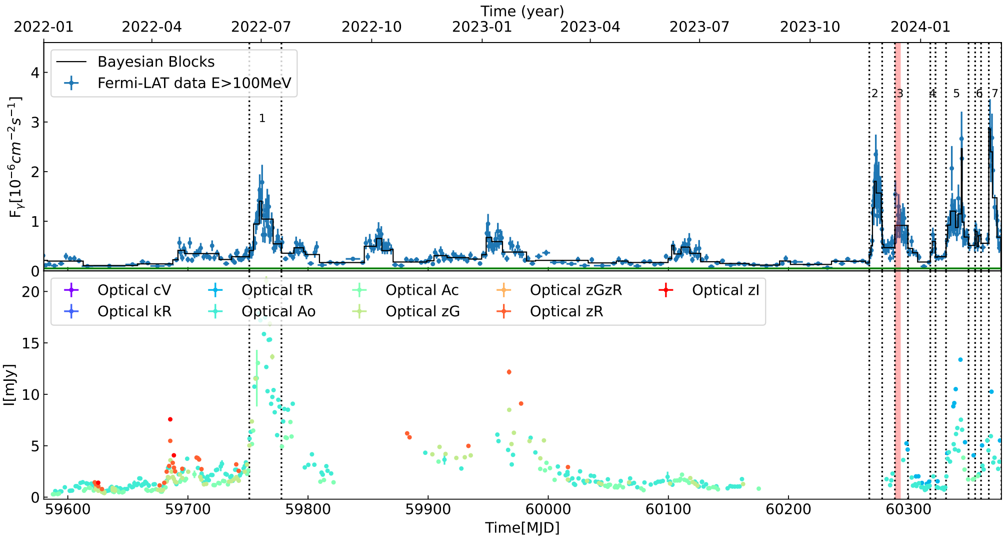


Figure 2: *Fermi*-LAT (top) and Optical (bottom) lightcurves from the 1st of January 2022 to 9th of March 2024. The dashed black lines indicate the brightest γ-ray flaring periods in which we want to focus. We didn't include the flaring periods between the 18th of July 2022 and the 19th of December 2023 because their average flux is smaller than the value found for the flaring periods in 2023 and 2024, except for the fourth and the sixth ones. Hence, the fourth and sixth flaring periods are not among the highest ones, but they were included because they happened between the two ATels [4] and [6]. For each γ-ray flare, there seems to be a corresponding optical flare. The red vertical bands represent the period in which OP 313 was detected by LST-1 at La Palma.

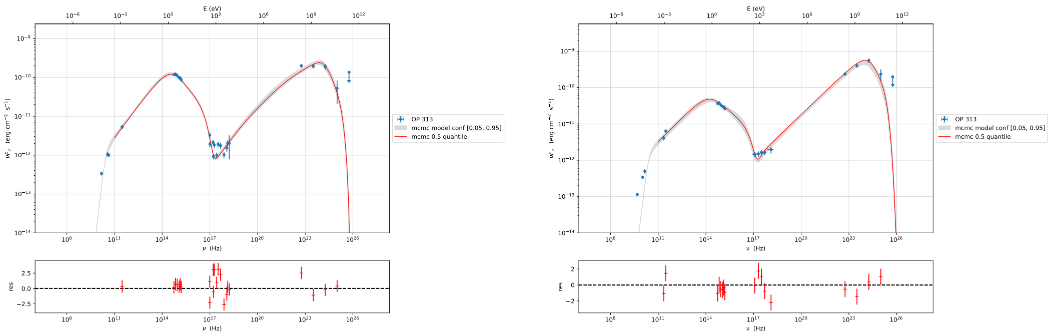
4. Results

The number of γ-ray photons seen by Fermi-LAT is large enough to study the hysteresis patterns [7] for the identified highest γ-ray flares. The hysteresis pattern gives information about the acceleration and cooling rates of the particles in the blazar's jet. There are two different kinds of hysteresis patterns: clockwise and anti-clockwise patterns. We found both of them for different flares in the time window 2022 - 2024: the Flare 1 showed an anti-clockwise hysteresis pattern, while the Flare 2 and 5 showed a clockwise hysteresis pattern.

We compared the Spectral Energy Distributions (SEDs) of the selected different flares to identify the difference in the heights of the 2 peaks of the SEDs. The heights of the peaks of a blazar's SED are linked to the Comptonization [8]. The highest γ-ray 2022 flare SED peaks have the same height, while the ones from November 2023 have different heights. Hence, we can hypothesize that different photon fields are involved in the flaring activity of the source from 2022 to 2024.

To prove this, we analyzed the time variability of the multi-frequency SED to understand the physical processes driving the flaring activity of OP 313. Specifically, we focused on two flaring periods: the first (July 2022) and the fifth (January 2024), as they exhibit different behaviors in terms of Comptonization. For the modeling and fitting of the two radiative states of OP 313, we have used the JetSeT framework [9–11]. The observed fluxes for both flaring periods at high energy are well explained by a single-zone model with Synchrotron Self-Compton (SSC) and External

Compton (EC) emission mechanisms. In both cases, the EC dominates over the SSC emission, suggesting that photon fields outside the jet are responsible for the Inverse Compton (IC) scattering, in our case from the Dusty Torus (DT), as expected from [12]. Furthermore, starting from the best-fit models, we used the `JetSet McmcSampler` interface to perform a Monte-Carlo-Markov chain (MCMC). Our goal was to sample the space parameters of the 2 flaring periods. The two resulting models with their confidence levels are shown in Figure 3(a) and 3(b). More details on this part will be presented in a dedicated publication.



(a) (b)

Figure 3: (a) Model-fit broadband SED of OP 313's Flare 1 and (b) model-fit broadband SED of OP 313's Flare 5 using `JeTSet McmcSampler`. The legends provide the colour coding for the MCMC information.

The results of the publicly available visibilities of the MOJAVE and VLBA-BU-BLAZAR (VLBA-BU-BLAZAR) programs from 1995 to 2018 are published in [13], [14], and [15]. From 2019 to 2024, the analysis was carried out by us and, as a result, a new jet component appeared starting from the 13th of April 2021 in MOJAVE. The same component was also discovered in the VLBA-BU-BLAZAR. We argue that this component can be responsible for the flaring emission that started in 2022.

5. Conclusions

OP 313 is an FSRQ characterized by a remarkable flaring activity starting from November 2023. We studied the long-term multi-wavelength emission of this object starting from the beginning of the *Fermi* mission in August 2008. From the multi-wavelength light-curves, we found hints of correlations between the γ-ray emission, the X-ray, the UV, and optical emission. In contrast, the radio emission exhibited a peak in 2008, likely linked to a γ-ray flaring event that occurred prior to the initiation of the Fermi-LAT mission. Subsequently, the radio emission began to increase again around 2019. Focusing on the γ-ray flaring activity, we identified the highest γ-ray flares and we reconstructed the hysteresis patterns to investigate the cooling mechanism and acceleration rates in the jet during the flares. Furthermore, we compared the SED of the flaring period height of the SED peaks during flares to understand which flare was more Compton dominated than the other. We modeled the SEDs of the first and fifth flaring periods using an SSC and EC single-zone model. This analysis shows that the EC-DT component is more prominent in the fifth flaring period SED, as expected. Finally, we did a VLBA analysis of the public visibilities of the MOJAVE and VLBA-BU-BLAZAR to see if new components, arising in the jet, can be responsible for the observed flaring emission.

More details and insights on the analysis of OP 313 and its interpretation will be presented in a dedicated publication.

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