Spectral Studies of Flaring FSRQs at GeV Energies Using Pass 8

Fermi-LAT Data

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Flat spectrum radio quasars (FSRQs) are bright active galactic nuclei surrounded by gas clouds within a UV-visible intense radiation field that form the so-called broad line region (BLR). These objects emit relativistic jets from a region close to the central supermassive black hole and through the BLR. The Fermi-Large Area Telescope (Fermi-LAT) is sensitive to gamma-ray photons from ~30 MeV to more than 300 GeV. We have performed spectral analysis of bright FSRQs in a 5.5 year (2008-2014) data sample collected by Fermi-LAT, using the new Pass 8 event selection and instrument response function. Also, our study of flaring episodes in a limited time range brings interesting results while compared to the full 5.5 year data samples.

1. Modelling the BLR radiation field

FSRQs constitute a class of active galactic nuclei (AGNs) with a dense BLR in which gamma rays with energy $\gtrsim 10$ GeV are absorbed due to electron-positron pair creation, if produced deep inside the BLR. Indeed, BLR is expected to be denser in FSRQs compared to the BL Lac class.

Operating since 2008, the Fermi satellite has amassed more than 6 years of data, continuously surveying the whole sky. The sensitivity of Fermi-LAT is ideal for the study of the gamma-ray absorption inside FSRQs in the 100 MeV-300 GeV range. From constraints on gamma-ray absorption we may infer limits on the location of the gamma-ray emission region in the FSRQ jets.

We expect $>10$ GeV photons of FSRQs to undergo absorption in the BLR, where the target photon with energy $\epsilon$ is a UV photon from the BLR radiation field. As most of these photons are expected to come from the emission lines, we use a model that includes the 6 strongest lines (NV, Lyα, OVI Lyβ, CII NII, NeVIII OIV, HeII Lyα) between $\sim 10$ to 41 eV.

We model these lines using a Breit-Wigner distribution, given by:

$$BW(\epsilon) = \frac{n_i \omega_i}{2 \pi [(\epsilon - \epsilon_i)^2 + (\omega_i/2)^2]}, \quad (1)$$

where $n_i$ and $\omega_i$ are the number density and width, respectively, for a given line $i$.

Under the commonly used relations $L_{BLR} = 0.1 L_{disc}$ and $R_{BLR} = \sqrt{L_{disc}}$, where $L_{BLR}$ is the luminosity of the BLR, $R_{BLR}$ its radius, and $L_{disc}$ the luminosity of the accretion disc. The photon density $n_i$ of the radiation field for each line $i$ can be written:

$$n_i[cm^{-3}] \simeq 1.66 \times 10^{11} \left( \frac{L_i}{10^{45} erg \ s^{-1}} \right) \left( \frac{10^{17} cm}{\epsilon_i, eV R_{BLR}} \right). \quad (2)$$

The opacity is derived from and is expressed as a function of $E$ and $z$:

$$\frac{d\tau_{\gamma\gamma}(E, z)}{dx} = \frac{\omega_0}{2} \left[ \frac{m^2 c^4}{E(1+z)} \right]^2 \times \sum_{i=1}^{6} \left( n_i \omega_i \right) \frac{\varphi \left[ \frac{\epsilon E(1+z)}{m^2 c^2} \right]}{\left( \epsilon - \epsilon_i \right)^2 + \left( \omega_i/2 \right)^2} \left( 4 \right)$$

where $r_0$ is the classical electron radius, $m$ the electron mass.

The $\tau_{\gamma\gamma}$ opacity in the BLR is then calculated as following:

$$\tau_{\gamma\gamma}(E, z) = a \times R_{BLR} \times \frac{d\tau_{\gamma\gamma}}{dx}(E, z), \quad (4)$$

assuming the gamma rays are produced within $a \times R_{BLR}$, where $R_{BLR}$ is the outer radius of BLR, and $a < 1$. Since this absorption happens at some distance from the supermassive black hole, this corrective factor that we called "$a$" represents the fraction of the BLR responsible for the absorption.

In Table I are displayed the line properties of the average spectrum of quasars we used in our model, as they were given in [13]. Since the He II Lyα line has quite large uncertainties, we arbitrary fixed its EW and relative flux to be equal to the ones of N V (uncertainty represented by *)

Very high energy gamma rays travelling from far distances undergo absorption in the extragalactic background light ("EBL", mainly composed of infrared-UV radiation). This absorption is to be considered above 10 GeV and has been implemented in our studies, from the model presented in [6].

Evidence of absorption in the BLR for some FSRQs have been reported in [11, 12].
Table I: Properties of 5 main lines of the average spectrum of quasars as compiled in [13], and He II Lyα as we defined it for this study.

| Line    |  e (eV) | EW (eV) | Relative Flux |
|---------|---------|---------|---------------|
| NV      | 10.0    | 0.16    | 0.22          |
| Lyα     | 10.2    | 0.71    | 1.00          |
| OVI Lyβ | 12.04   | 0.19    | 0.191         |
| CIII NIII | 12.65  | 0.09    | 0.081         |
| Ne VIII OIV | 15.90 | 0.08    | 0.047         |
| HeII Lyα | 40.81  | 0.16*   | 0.22*         |

2. Data processing and model fitting

We have analysed data of 7 bright gamma-ray FSRQs. Plots of the spectral energy distributions (SEDs) under the label “5.5 years” have been processed from 4 August 2008 till 30 April 2014. The sources we present in this paper are listed in Table I, LII and BII being respectively the Galactic latitude and longitude in decimal degrees.

Data were processed using the Pass 8 data representation (P8_SOURCE_V4), and the Science Tools version v9-34-01. Signal is reconstructed from each source using the unbinned likelihood tool1, applied to LAT data in the 0.1-300 GeV energy range, within a region of interest (ROI) of 10° radius. A source region extended to an additional 10° annulus accounted for all the point sources of the Second Fermi-LAT source catalog, and for the Galactic diffuse emission (template_4years_P8_V2_scaled) and the isotropic diffuse emission (isotropic_source_4years_P8V3).

We computed the SEDs for all the sources of the selected sample with the Pass 8 data representation. Additionally, for the two brightest objects of our FSRQ sample, i.e. 3C 454.3 and PKS 1510-089, we also computed the SEDs with the PASS 7 reprocessed dataset (P7REP_SOURCE_V15) and verified the consistency of the results with respect to the PASS 8 ones. Although some bin-to-bin fluctuations appear due to energy wise event migrations, the two SEDs (Pass 7 and Pass 8) for both the sources are compatible (as shown in Figure 2 for 3C 454.3).

A first set of fits was performed from 100 MeV till the highest energy data point (excluding upper limits), using a log-parabola (LP: \( dN(E)/dE = N_0 (E/E_0)^{-\alpha - \beta \log(E/E_0)} \)), with \( E_0 \) kept fixed at 297.6 MeV, and where “log” is the natural logarithm), a broken power law (BPL: \( dN(E)/dE = N_0 (E/E_b)^{-\Gamma_i} \)), with \( i = 1 \) if \( E < E_b \) and \( i = 2 \) if \( E > E_b \), and a power law with an exponential cutoff (PLEC: \( dN(E)/dE = N_0 (E/E_p)^{-\Gamma_{PLEC}} \exp(-E/E_c) \), with \( E_p \) kept fixed at 412.7 MeV). Other sets of fits were performed by adding exponential factors to model the EBL absorption and the opacity of the BLR.

As the fits presented in the Sections 2 and 3 are binning dependant, the values of the fit parameters vary from one choice of binning to another. Narrow data binning could hold spurious fluctuations, while wide data-binning could hide features. In order to estimate this systematic effect, we do the following: a first LP fit is performed on the SED, while keeping all parameters fixed to the values obtained by the unbinned likelihood analysis, and a \( \chi^2/ndf \) is returned. A second LP fit is performed with \( N_0, \alpha \) and \( \beta \) kept free,
Table II Characteristics of the 7 FSRQs used in this paper. Sources are ordered by decreasing flux in the 1-100 GeV energy range. Values of the luminosity in the broad line region \((L_{BLR})\) are taken or derived from [10, 14].

| Name          | RA (J2000.0) | Dec (J2000.0) | LII (deg.) | BII (deg.) | Redshift \(z\) | Flux 2FGL 1-100 GeV | Flux 1FHL 10-100 GeV | Photon index 1FGL | \(L_{BLR}\) (10^{44}erg s^{-1}) |
|---------------|--------------|---------------|------------|------------|-----------------|---------------------|---------------------|--------------------|---------------------|
| 3C 454.3      | 22 53 57.7   | +16 08 53.1   | 86.11      | -38.19     | 0.859           | 9.65e-8              | 1.35e-9              | 2.46619            | 33.00               |
| PKS 1510-08   | 15 12 50.5   | -09 06 00.9   | 351.28     | 40.13      | 0.360           | 4.06e-8              | 7.35e-10             | 2.40756            | 5.62                |
| 4C +21.35     | 12 24 54.5   | +21 22 46.9   | 255.08     | 81.65      | 0.434           | 3.54e-8              | 7.43e-10             | 2.54717            | 15.80               |
| 3C 279        | 12 56 11.0   | -05 47 20.1   | 305.1      | 57.06      | 0.536           | 2.56e-8              | 5.37e-10             | 2.32061            | 3.10                |
| PKS 0454-234  | 04 57 03.1   | -23 24 52.0   | 223.7      | -34.9      | 1.003           | 2.27e-8              | 2.99e-10             | 2.20649            | 3.70                |
| B2 1520+31    | 15 22 09.8   | +31 44 14.3   | 50.16      | 57.02      | 1.484           | 1.76e-8              | 4.27e-10             | 2.42125            | 8.00                |
| PKS (B)1424-41| 14 27 56.2   | -42 06 18.6   | 321.44     | 17.26      | 1.522           | 1.47e-8              | 2.9e-10              | 2.31004            | 8.91                |

We would consider having evidence for absorption in the BLR if we get all of the following:

- at least one good quality fit among one of the fits with EBL+BLR absorption (LP\(\tau\), BPL\(\tau\) and PLEC\(\tau\));
- parameter “a” with a relatively small error bar;
- a small p-value or a bad fit of the corresponding function with only EBL absorption (LP, BPL or PLEC).

In Table III are displayed the fit parameters of the 7 sources, along with the p-values used to compare the models (with versus without absorption). In blue bold face are the parameters that suggest a possible BLR absorption, as some of the above conditions are partially met for 3C 454.3 (with a p-value of \(6 \times 10^{-4} / 3.9 \sigma\) C.L.), and for TXS 1520+31 (with a p-value of \(9.3 \times 10^{-3} / 2.6 \sigma\) C.L.). We have no hint of absorption for the other sources we studied.

4. Results on high state/flaring episodes

Data were analysed during flaring/high state periods for the following sources:

- 3C 454.3 (high state and giant flare) during 02 Nov-05 Dec 2010 (MJD 55502.5-55535.5);[1]
- PKS 1510-089 during 19 Feb-04 Apr 2012 (MJD 55976.0-56021.0), along with MAGIC data from the same period (MAGIC data points taken from[2]);
- PKS 1424-41 during 30 Sep 2012-27 Jul 2013 (MJD 56200.0-56500.0), as a combined series of 4 successive radio flares).

During these outburst episodes, the gamma-ray emission region can have a different location compared...
to the quiescent state. In this section we present the results obtained on these three high states (Figure 4 and Table IV). Under the same criteria than the ones used in Section 3, we still find no evidence of BLR absorption, though we still have a hint of it for 3C 454.3 with a p-value of around $2 \times 10^{-3}$ for the discrepancy between the BPL and BPL$\tau$ fits (significance of about 3 $\sigma$). Due to the unusual shape of the SED of PKS 1424-41 during this series of 4 flares, all fits have a large $\chi^2$ value.

Though we dispose of less photons in the data analysis of flaring episodes, during strong and long flares, it could be possible to constrain the location of the gamma-ray production region if it is deep enough inside the BLR.

Figure 3: SEDs of 3C 454.3, PKS 1510-089, TXS 1520+31 and PKS 1424-41. BPL and PLEC fits are often hidden beneath BPL$\tau$ and PLEC$\tau$. 
Figure 4: SEDs of 3C 454.3, PKS 1510-089 and PKS 1424-41 during the outburst periods. PLEC fits are hidden beneath PLECτ for 3C 454.3 and PKS 1424-41. The flare of PKS 1510-089 was studied along with MAGIC data above ~90 GeV and the combined LAT-MAGIC SED was fitted only with LP and LPτ function (LP hidden beneath LPτ).

5. Conclusions and perspectives

We find that the gamma-gamma absorption in the BLR is not significant enough to claim discovery for the models of BLR and spectral functions we have investigated. There are hints of absorption in case of 3C 454.3 and TXS 1520+31 with significance of the order of 3σ. An implication of our results could be that the gamma-ray emission zone in FSRQs might be located outside or at the outer edge of the BLR. However, further investigation on binning effects on the SED fits are required. Future work is also expected to improve the modelling of the BLR.

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### Table III: Fitting parameters and derived significances for the 7 bright FSRQs of our sample.

We mention (*) when a parameter is fixed at its lower limit.

| Parameter | Model | PKS 1510-089 | 4C +21.35 | 3C 279 | PKS 0454-234 | TXS 1520+31 | PKS1424-24 |
|-----------|-------|--------------|-----------|--------|---------------|--------------|--------------|
| $\chi^2$/ndf | **without abs. model** | | | | | | |
| $\chi^2$/ndf | **without abs. model** | | | | | | |
| $\Delta \chi^2$ (ndf) | | | | | | | |
| p-value | | | | | | | |
Table IV  Fitting parameters and derived significances for the 3 flares we studied in our FSRQ sample. We mention (*) when a reached the lower edge of the fitting interval.

| Parameter          | Model                 | 3C 454.3     | PKS 1510-089 | PKS1424-24 |
|--------------------|-----------------------|--------------|--------------|------------|
|                    | (Nov-Dec 2010)        | (Feb-Apr 2012) | (Sep 2012-Jul 2013) |
| 5th Fermi Symposium: Nagoya, Japan: 20-24 Oct, 2014 | | | | |
| LP\_unbinned α     | 2.152 ± 0.008         | 2.268 ± 0.27 | 2.022 ± 0.10 |
| LP\_unbinned β     | 0.0895 ± 0.0036       | 0.0451 ± 0.0108 | 0.0766 ± 0.0052 |
| PL E_b              | 286 ± 8.9             | 260 ± 6.0    | 940 ± 35.4  |
| LP α               | 2.153 ± 0.016         | 2.299 ± 0.040 | 2.069 ± 0.014 |
| LP β               | 0.0879 ± 0.0088       | 0.0569 ± 0.0117 | 0.1134 ± 0.0120 |
| BPL Γ_1            | 2.140 ± 0.022         | 2.367 ± 0.038 | 2.010 ± 0.003 |
| BPL Γ_2            | 2.617 ± 0.036         | 2.867 ± 0.076 | 2.530 ± 0.055 |
| BPL E_b            | 921 ± 0.4             | 2603 ± 912.7 | 3062 ± 1.6  |
| PLEC Γ_PLEC        | 2.183 ± 0.034         | 2.269 ± 0.049 | 1.903 ± 0.021 |
| PLEC E_c           | 9981 ± 2111.4         | 7921 ± 2586.5 | 8361 ± 1117.7 |
| LP τ α             | 2.157 ± 0.018         | 2.299 ± 0.022 | 2.069 ± 0.014 |
| LP τ β             | 0.0764 ± 0.0116       | 0.0569 ± 0.0065 | 0.1134 ± 0.0120 |
| BPL τ Γ_1          | 2.156 ± 0.029         | -             | 1.900 ± 0.019 |
| BPL τ Γ_2          | 2.518 ± 0.050         | -             | 2.426 ± 0.036 |
| BPL τ E_b          | 921 ± 0.2             | -             | 1375 ± 0.2  |
| PLEC τ Γ_PLEC      | 2.183 ± 0.034         | -             | 1.903 ± 0.021 |
| PLEC τ E_c         | 9983 ± 2113.2         | -             | 8361 ± 1135.7 |
| a                  | 0.00703 ± 0.00551     | 0.04667 ± 0.04550 | 0.00001 ± 0.00132 |
|                    | 0.01059(0.00591)      | -             | 0.00001 ± 0.00320 |
|                    | 0.00001 ± 0.000629    | -             | 0.00001 ± 0.00108 |
| χ²(ndf) without abs. model | LP\_unbinned | 4.553 (14)    | 67.828 (17)  | 79.634 (15) |
|                    | LP                      | 4.041 (11)    | 20.807 (14)  | 37.481 (12) |
|                    | BPL                     | 13.158 (10)   | 15.137 (13)  | 101.358 (11) |
|                    | PLEC                    | 6.912 (10)    | 37.461 (13)  | 77.643 (11)  |
| χ²(ndf) with abs. model | LP\_unbinned | 0.928 (10)    | 20.807 (13)  | 37.489 (11)  |
|                    | BPL                     | 3.780 (9)     | -             | 24.648 (10)  |
|                    | PLEC                    | 6.914 (10)    | -             | 77.652 (11)  |
| Δχ²(ndf)           | LP/PL                  | 3.113e+00     | 6.395e-11     | 7.583e-03    |
|                    | BPL/BPL                 | 9.378e+00     | -             | 7.671e+01    |
|                    | PLEC/PLEC               | 1.586e-03     | -             | 9.270e-03    |
| p-value            | LP/PL                  | 7.769e-02     | -             | -            |
|                    | BPL/BPL                 | 2.195e-03     | -             | -            |
|                    | PLEC/PLEC               | 0.000e+00     | -             | -            |
