TeV detection and insights into the emission regions of two gamma-ray fast flaring blazars

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Abstract.
The γ-ray blazars B2 1811+31 and GB6 J1058+2817 exhibited strong flaring activity in 2020 and 2021, respectively. These high states were observed by the Large Area Telescope on board the *Fermi Gamma-ray Space Telescope* in the high-energy (HE; 100 MeV $< E <$ 100 GeV) γ-ray band, triggering observations in the very-high-energy (VHE, $E >$ 100 GeV) γ-ray band with the MAGIC telescopes, in UV and X rays with the *Neil Gehrels Swift Observatory* and in the radio and optical bands with many ground-based telescopes. MAGIC telescopes observations led to the first detection at VHE of both sources. In this contribution, we present the details of these detections and the results of an extensive study of the high-state properties of the two blazars. *Fermi*-LAT data were used to derive long-term γ-ray light-curves and identify the periods of enhanced activity in both sources. We investigated their spectral properties and temporal variability, with focus on how the strong spectral hardening and the variability timescale can provide information on the γ-ray emitting regions during the flare.

1 Introduction

Blazars are the most numerous γ-ray sources in the extra-galactic sky in both the high-energy (HE; 100 MeV $< E <$ 100 GeV) and very-high-energy (VHE; $E >$ 100 GeV) γ-ray bands. They are jetted active galactic nuclei (AGN) with jets of plasma lying at small angles from the line of sight from the Earth. The radiation from blazars extends from radio to γ-ray energies and it is highly beamed and boosted by relativistic effects. In addition, they show rapidly variable emissions at all wavelengths.

According to the features of the optical/UV spectra, blazars can be classified into two categories. In the optical/UV band, flat-spectrum radio quasars (FSRQs) show the presence of strong emission lines, in addition to a thermal component associated with the accretion disk. Differently, the optical/UV spectra of BL Lac objects (BL Lacs) show no or weak lines. This property makes the evaluation of the redshift of these sources particularly challenging [1].

The spectral energy distribution (SED) of blazars exhibits a non-thermal continuum composed by two main bumps [2]. The low-energy SED bump peaks in the frequency range from infrared to X rays and it is usually interpreted as synchrotron emission from relativistic electrons accelerated within the jet. The high-energy bump peaks above MeV energies and it is commonly attributed to inverse Compton (IC) scattering of low-energy photons. The seed photons for the IC scattering can be produced within the jet via synchrotron radiation (synchrotron self-Compton, SSC) but they can also originate externally to the jet; the latter case is often referred to as external Compton (EC). Commonly, SSC scenarios are preferred to describe the broad-band SEDs of BL Lacs, due to the low intensity of photon fields external to the jet. The high-energy bump of FSRQs is instead generally modeled in terms of the EC off thermal photons from the accretion disk or reprocessed disk radiation from the broad-line region or dusty torus. Hadronic scenarios have also been employed to model blazars emissions, supported by the evidence by the IceCube Neutrino Observatory of AGN as possible neutrino source candidates [3].

The peak frequency ν_s of the synchrotron bump in the SED leads to a further classification of BL Lacs into low-, intermediate-, and high-frequency peaked sources (LBL, $\nu_s < 10^{14}$ Hz, IBL, 10^{14} Hz $< \nu_s < 10^{15}$ Hz and HBL, $\nu_s > 10^{15}$ Hz, respectively [4]). The classification based on ν_s can be extended to the whole blazars category. Low-, intermediate- and high-synchrotron-peaked (LSP, ISP and HSP, respectively) objects can be defined in analogy with the classification for BL Lacs. Most of the TeV emitting BL Lacs are HBLs, with only few IBLs and LBLs detected at VHE γ rays. In addition, most FSRQs are LSP blazars.

The blazars B2 1811+31 ($z = 0.117$ [5]) and GB6 J1058+2817 ($z = 0.4793$, tentative value [6]) are classified as BL Lac objects in the *Fermi*-LAT Fourth Source Catalog [7]. In particular, B2 1811+31 is reported to be an IBL, whereas GB6 J1058+2817 is classified as a BL Lac of unclear class. Triggered by flaring activities in the HE γ-ray band reported by the *Fermi*-LAT, respectively on MJD 59124 (October 2, 2020) and MJD 59302 (March 29, 2021) [8, 9], MWL follow-up campaigns on the two sources were organized. The MAGIC telescopes joined both observational campaigns and detected for the first-time VHE γ-ray emission from B2 1811+31 and GB6 J1058+2817 [10, 11]. Further MWL coverage was provided by the instruments onboard the *Neil Gehrels Swift* Observatory at optical/UV and X rays. Several observatories in the optical and radio bands joined the follow-up observational campaigns. In this contribution, we present details of the analyses of the observations carried out by the MAGIC telescopes and the *Fermi*-LAT on B2 1811+31 and GB6 J1058+2817.

2 Very-high-energy γ-ray observations

MAGIC is a stereoscopic system of two 17 m diameter imaging atmospheric Cherenkov telescopes located at an altitude of 2200 m at the Roque de los Muchachos Observatory in La Palma [12]. MAGIC observed in dark conditions B2 1811+31 from MJD 59127 (October 5, 2020) to MJD 59133 (October 11, 2020) over a wide zenith angle range, from 20° to 65°, while GB6 J1058+2817 was observed from MJD 59306 (April 2, 2021) to MJD 59309 (April 5, 2021) at low zenith distance, from 5° to 35°. The analysis was performed with the standard MARS software for the MAGIC analysis [13].

The presence of a significant γ-ray excess from the sources with respect to background was investigated through the standard θ^2 variable, which is defined as the squared angular distance of the reconstructed direction of the shower with respect to the source direction. In the previously mentioned observations, B2 1811+31 and GB6 J1058+2817 were detected with a Li&Ma [14] significance of $5.3\,\sigma$ and $6.0\,\sigma$, respec-

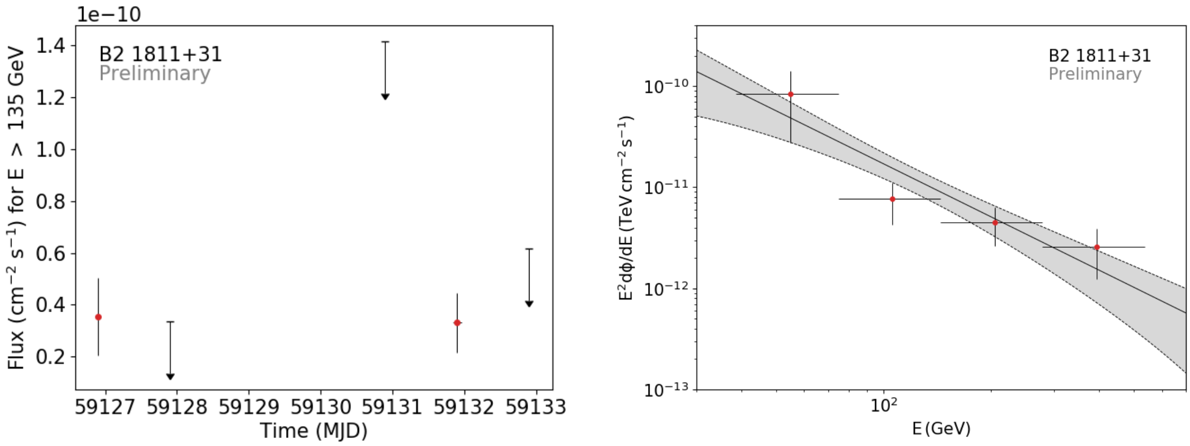

Figure 1: *Left:* night-wise light curves in the VHE γ-ray energy range for B2 1811+31. 95% confidence upper limits are indicated as downward arrows. *Right:* VHE γ-ray SED of B2 1811+31 (left) measured by MAGIC and corrected for EBL extinction effects (red circles).

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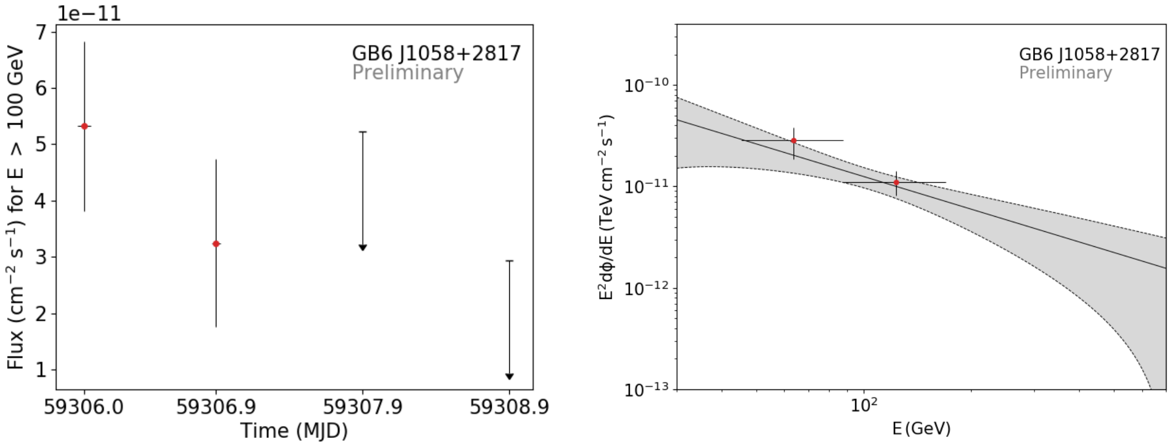

Figure 2: *Left:* night-wise light curves in the VHE γ-ray energy range for GB6 J1058+2817. 95% confidence upper limits are indicated as downward arrows. *Right:* VHE γ-ray SED of GB6 J1058+2817 (left) measured by MAGIC and corrected for EBL extinction effects (red circles).

tively. The night-wise light-curves at energies above 135 and 100 GeV were derived. The energy threshold was chosen for a proper flux estimation for each source while accounting for the observational conditions. The left panels of Figures 1 and 2 show the VHE γ-ray light-curve of B2 1811+31 and GB6 J1058+2817, respectively, reconstructed from the MAGIC observations.

The data acquired during multiple nights were combined to evaluate the overall spectrum, since the acquired signal was not intense enough to evaluate the spectrum for each night. The observed spectra were unfolded by the energy dispersion using the Bertero method [15] and then corrected for the extragalactic background light (EBL) absorption by adopting the Domínguez model [16] in order to reconstruct the intrinsic spectra. These are well described with power laws

$$\frac{dN}{dE} = N_0 \left(\frac{E}{E_0}\right)^{-\Gamma} \tag{1}$$

with photon index $\Gamma = 3.75 \pm 0.40_{\rm stat}$, decorrelation energy $E_0 = 125.16\,\rm GeV$ and normalization constant $N_0 = (7.36 \pm 1.99_{\rm stat}) \times 10^{-10}\,\rm TeV^{-1}\,cm^{-2}\,s^{-1}$ for B2 1811+31, and $\Gamma = 3.39 \pm 0.32_{\rm stat}$, $E_0 = 161.11\,\rm GeV$ and $N_0 = (1.95 \pm 0.54_{\rm stat}) \times 10^{-10}\,\rm TeV^{-1}\,cm^{-2}\,s^{-1}$ for GB6 J1058+2817. The VHE γ-ray SEDs of B2 1811+31 and GB6 J1058+2817 reconstructed from the MAGIC observations are shown in the right panels of Figures 1 and 2, respectively.

3 High-energy γ-ray observations

The Large Area Telescope (LAT) instrument onboard the *Fermi Gamma-Ray Space Telescope* is a pair-conversion space-based telescope sensitive to γ rays from tens of MeV to about 1 TeV [17]. The *Fermi* satellite completes an orbit roughly every 90 minutes. The standard operating mode of *Fermi*-LAT is the survey one. Its field of view of 2.4 sr ensures $\sim 20\%$ coverage of the entire sky at any given time.

The dataset considered for the analysis of B2 1811+31 and GB6 J1058+2817 data consisted of data from the beginning of the mission in 2008 up to 2023. The analysis was carried out using the ScienceTools v2.0.8 and `fermipy` v1.0.1 [1]. We used photon events from the SOURCE class in the $100\,\rm MeV - 1\,TeV$ energy range and the P8R3_SOURCE_V2 instrument response function. Standard prescriptions for analyses of *Fermi*-LAT data were employed, i.e. `'DATA_QUAL>0 && LAT_CONFIG==1'`, zenith distance $< 90^\circ$ to reduce the Earth limb contamination. The observed events with reconstructed directions around 15° from the sources' positions were fitted using a binned maximum-likelihood method with a model composed of the nearby localized 4FGL sources as well as of the Galactic and isotropic diffuse backgrounds.

In order to investigate the HE γ-ray variability of the two sources of interest, we produced light curves with equally-spaced time bins. A dedicate likelihood analysis in each temporal bin was performed. The light-curves clearly show periods of enhanced activity corresponding to the *Fermi*-LAT triggers for the

[1] `https://fermipy.readthedocs.io/en/latest/`

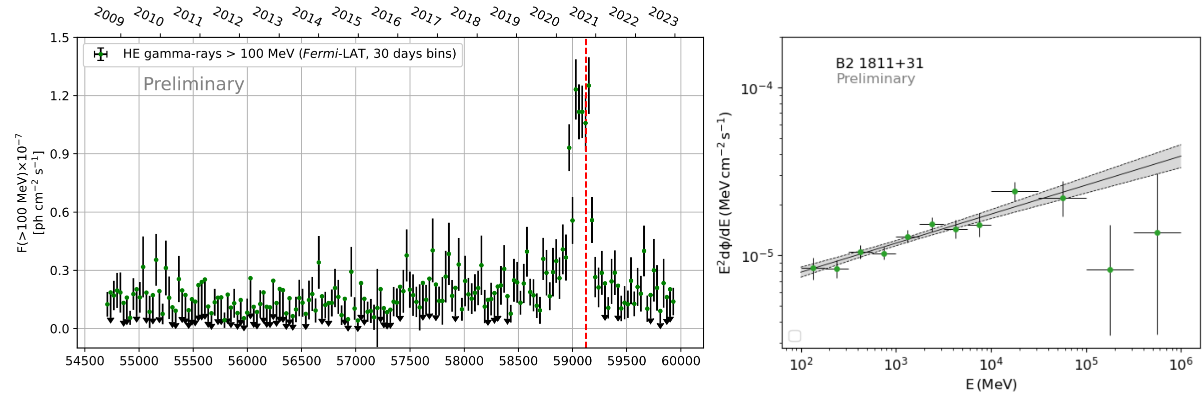

Figure 3: *Left:* γ-ray flux light-curve of B2 1811+31 measured with the *Fermi*-LAT since the beginning of the mission, bi-weekly binned. The red dashed line marks the *Fermi*-LAT trigger on MJD 59124 (October 2, 2020). 95% C.L. upper limits are shown as downward arrows for each time bin where the TS value for the source was found to be smaller than 9. *Right*: HE γ-ray SED of B2 1811+31 as measured by the *Fermi*-LAT in the MJD 58940 − 59190 period.

two sources. The left panels of Figures 3 and 4 show the long-term *Fermi*-LAT light-curves of B2 1811+31 and GB6 J1058+2817 respectively, using bins of 30 days.

The spectral features of the two sources in the time intervals before, during and after the flare were analysed by performing dedicated fit. In the flare periods, the spectra of both sources are well described by a power-law model (Equation 1), with spectral index $\Gamma = 1.83 \pm 0.02$ for B2 1811+31 and $\Gamma = 1.81 \pm 0.04$ for GB6 J1058+2817, both hardening with respect to the quiescent states. In 4FGL, the average HE γ-ray spectral photon indices are equal to $\Gamma = 2.17$ and $\Gamma = 2.23$ for B2 1811+31 and GB6 J1058+2817 respectively. The right panels of Figures 3 and 4 show the HE γ-ray SED from B2 1811+31 and GB6 J1058+2817 during the periods of enhanced γ-ray activity in 2020 and 2021, respectively.

4 Conclusions

As the emissions from blazars are extremely variable and span the entire electromagnetic spectrum from radio to VHE γ rays, MWL simultaneous observations are a unique tool to infer insights into the dynamical processes occurring within the source environments, especially during high state periods.

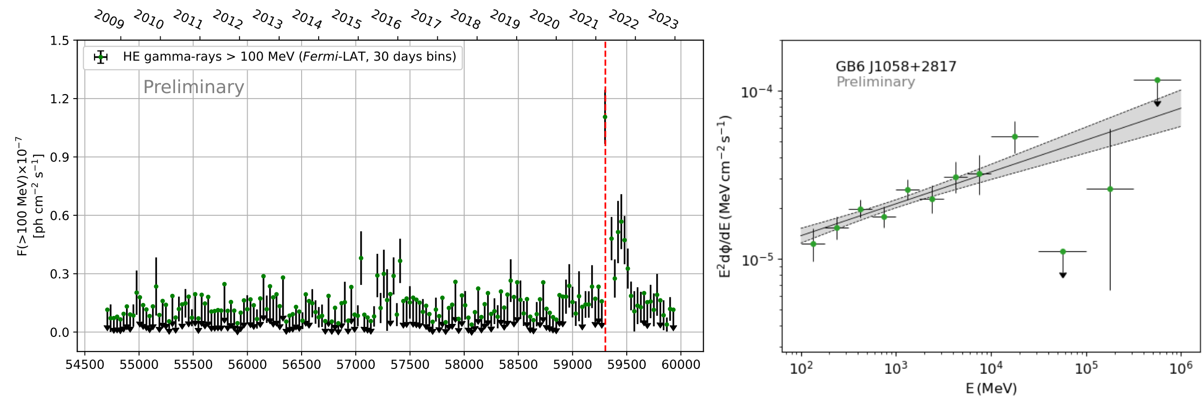

Figure 4: *Left:* γ-ray flux light-curve of GB6 J1058+2817 measured with the *Fermi*-LAT since the beginning of the mission, bi-weekly binned. The red dashed line marks the *Fermi*-LAT trigger on MJD 59302 (March 29, 2021). 95% C.L. upper limits are shown as downward arrows for each time bin where the TS value for the source was found to be smaller than 9. *Right*: HE γ-ray SED of GB6 J1058+2817 as measured by the *Fermi*-LAT in the MJD 59300 − 59341 period.

In this contribution, we reported details of a MWL analysis performed on the BL Lacs B2 1811+31 and GB6 J1058+2817, both discovered at VHE γ rays by MAGIC during flaring periods triggered by *Fermi*-LAT. In literature, B2 1811+31 belongs to the category of IBLs, which are rare sources in the TeV sky, whereas GB6 J1058+2817 is classified a BL Lac of unclear class. In flaring state, both sources exhibited a soft VHE γ-ray spectrum, with spectra index ranging between 3 and 4 in this energy range. The observations in the *Fermi*-LAT range showed a quiescent state of both sources in the past, with a sudden increase in the HE γ-ray activity during the flare periods. In these time intervals, both sources showed strong flux enhancement and spectral hardening in HE γ rays with respect to observations carried out during low states.

Investigations of long-term MWL observations on the sources are ongoing, with a specific focus on the high-state periods, particularly in the optical/X-ray band in order to study the synchrotron peak position and properly classify the source states. Studies on the variability and multi-band cross-correlations of the sources are also ongoing, in order to constrain the size of the emission region dominating the radiative output during the high states and to gather info on the emission mechanisms dominating the radiative output from the sources. The MWL information will be employed to model the SEDs of the sources, in order to investigate the emission mechanism of this little studied subclass of blazars, which fills the gap between LBLs and HBLs, playing an important role for BL Lacs unification theories.

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