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Characterizing the VHE emission of the extreme HBLs 1ES 1218+304 and 1ES 0229+200 with VERITAS

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The modelling of the spectral energy distribution (SED) of some high-frequency peaked BL Lac objects (HBLs) has proved challenging for the so-called extreme candidates, which can have their TeV peak at energies >1 TeV and a hard intrinsic TeV spectrum of $\Gamma < 2$. The HBLs 1ES 1218+304 (z=0.182) and 1ES 0229+200 (z=0.1396) are two characteristic examples. Historically, leptonic one-zone synchrotron self-Compton (SSC) models have been used when modelling the broadband SED of BL Lac objects with relative success, but they fail to fully describe the emission of their extreme counterparts without requiring unexpectedly large or small physical quantities, or reaching far beyond the equipartition condition, when accounting for extragalactic background light (EBL). In this work, using archival VERITAS data from 2008 to 2021 on 1ES 1218+304 and 1ES 0229+200 combined with data from the *Swift*-XRT and *Fermi*-LAT observatories for extended wavelength coverage, we provide an updated look on the modelling of extreme HBLs.

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1. Introduction

The high-frequency peaked BL Lac objects (HBLs) 1ES 1218+304 (z = 0.182) and 1ES 0229+200 (z = 0.1396) are prototypical examples of the sub-sample of hard-TeV BL Lacs detected in the gamma-ray very-high energy (VHE) range, above 100 GeV. Their spectral energy distribution (SED) extreme observational properties, such as a gamma-ray peak at energies > 1 TeV and a hard intrinsic spectrum - after correcting for extragalactic background light (EBL) attenuation - with a spectral index $\Gamma_\gamma < 2$ make a compelling case when it comes to modelling their emission. The SEDs of HBLs have been described using a one-zone Synchrotron Self Compton (SSC) model [1] with relative success, but incoming data on these extreme HBL objects (EHBLs) challenges the SSC model predictions [2, 3], by requiring too large Doppler boosting factors ($\delta_D \gtrsim 50$) and conditions orders of magnitude beyond equipartition, i.e., the ratio between the electron energy density and the magnetic field energy density is larger than one. Due to the strength signal of these sources, one usually has to perform long-term, integrated analysis, or focus on sources' flares to reach satisfactory significance levels, often disregarding variability. This work approaches the subject of modelling EHBLs in a time-sensitive manner, using long-term VERITAS, *Fermi*-LAT and *Swift*-XRT data.

2. Data analysis

The VERITAS collaboration has collected ~ 180 h of exposure per source, spanning from 2008 to 2021. VERITAS data are pre-analyzed using collaboration standard packages [4, 5] to reduce data to DL3 products and then higher-level products such as spectra or lightcurves are produced using `gammapy` [6, 7]. VERITAS data are combined with *Fermi*-LAT, *Swift*-XRT and *Swift*-UVOT. *Fermi*-LAT data are analyzed using `fermipy` [8]. For the data analysis of *Swift*-XRT data, we use NASA's missions specific software [9].

3. Lightcurves

In Figures 1 and 2 the lightcurves from 1ES 0229+200 and 1ES 1218+304 are shown. In order to determine different flux states, we apply a Bayesian blocks algorithm [10], using the `astropy` [11] package, to compute point changes in the lightcurves. We also present the blocks determined by the algorithm with a requirement of 3 sigma for a point change. It is possible to notice that both VHE and X-ray bands are detected to be in different flux levels at different times.

In 1ES 0229+200 VERITAS and *Fermi*-LAT lightcurves a 6-monthly binning is used. 1ES 0229+200 source is dim through the gamma-ray HE and VHE ranges, therefore in order to better estimate the blocks lengths, larger integration windows are used. In 1ES 1218+304 VERITAS and *Fermi*-LAT lightcurves, a monthly binning is used instead. *Swift*-XRT is presented per observation since individual exposures are statistically significant. The upper limits are calculated for bins with TS < 4.

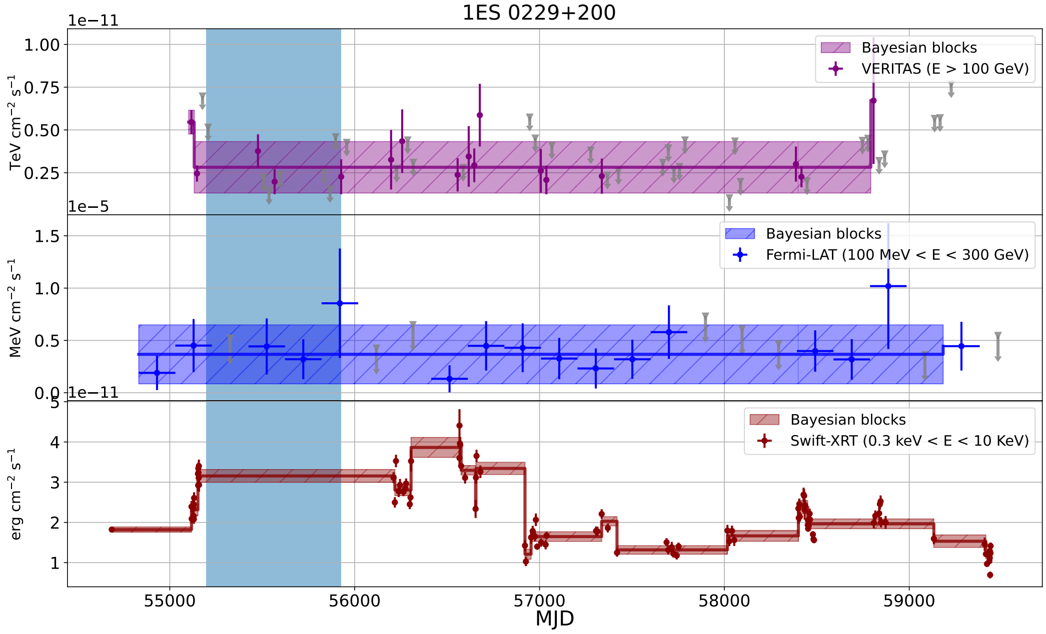

Figure 1: Multiwavelength lightcurve of 1ES 0229+200. VERITAS, *Fermi*-LAT, *Swift*-XRT lightcurves are shown, from top to bottom. The shaded blue region corresponds to the time interval used in [2].

4. 1ES 0229+200 variability

One important feature to observe in Fig. 1 is the change in the flux level at around 55465 MJD in the VERITAS lightcurve of 1ES 0229+200. We can study the effect on the Bayesian blocks of changing significance requirement for a change point. By calculating the bayesian blocks, requiring 1, 2, 3, 4 and 5 sigma significance for a change point, with 6-monthly binning, it is possible to notice that the the point change still holds at a 4 and 5 sigma level as shown in Fig. 3. This is relevant for studies that require a non-variable source (e.g., [13]).

5. SED modelling strategy

For the SED modelling, to minimize systematic errors from combining data with substantial observed variability, time intervals where no significant variability is detected in any band according to the MWL Bayesian blocks are identified. The stacked datasets from the VERITAS and *Fermi*-LAT observations are then created using `gammapy`, and the stacked energy spectrum from the *Swift* observations within that period is obtained. The MWL SED can now be fitted using a Markov Chain Monte Carlo (MCMC) approach, which is implemented in the `gammapy-recipes` library [1] with the use of the `emcee` package [14]. The one-zone leptonic SSC model SED is calculated using `agnpy` [15]. The model [1] consists of an emission region of size R_b (the blob) moving

[1]Available at
https://gammapy.github.io/gammapy-recipes/_build/html/notebooks/mcmc-sampling-emcee/mcmc_sampling.html

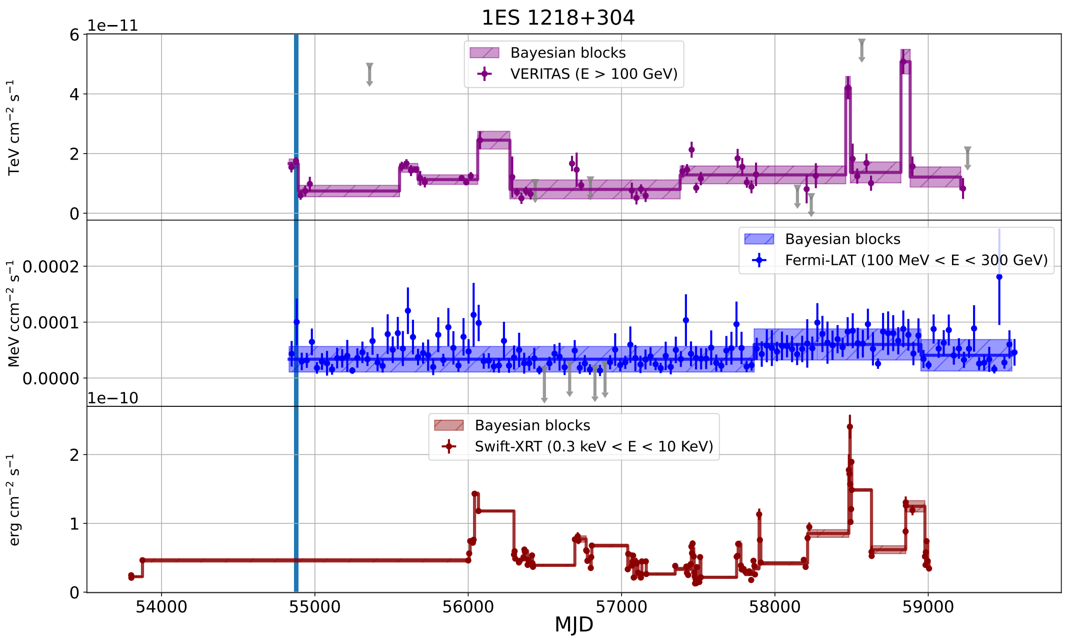

Figure 2: Multiwavelength lightcurve of 1ES 1218+304. VERITAS, *Fermi*-LAT, *Swift*-XRT lightcurves are shown, from top to bottom. The shaded blue region corresponds to the time interval used in [12].

relativistically in the blazar jet, containing an electron density distribution $n_e(\gamma)$, in the presence of a magnetic field of strength B emits Doppler boosted radiation by a factor δ_D, where

$$n_e(\gamma) = \begin{cases} n_0 \gamma^{-p_1}, & \gamma_{min} \leq \gamma \leq \gamma_b \\ n_0 \gamma^{-p_2}, & \gamma_b < \gamma \leq \gamma_{max} \end{cases} \tag{1}$$

and γ_{min} and γ_{max} are the minimum and maximum electron Lorentz factor, and γ_b is the transition Lorentz factor. p_1 and p_2 are the spectral indices before and after the break respectively. n_0 is the normalization factor, set to the total density of electrons in cm^{-3}. The size of the emission region R is constrained by the minimum variability observed t_{var}, the source's redshift z and the Doppler boosting factor δ_D

$$R = \frac{c \delta_D t_{var}}{1+z} \tag{2}$$

Efforts to produce SEDs in the time intervals of non-variable MWL flux are underway.

6. Conclusions

In this contribution, we propose a method to constrain the emission of EHBLs and sample the parameter space of our emission models, using the extensive VERITAS coverage in gamma-ray VHE band, as well as data from *Fermi* and *Swift*, taking into account the variability of the sources

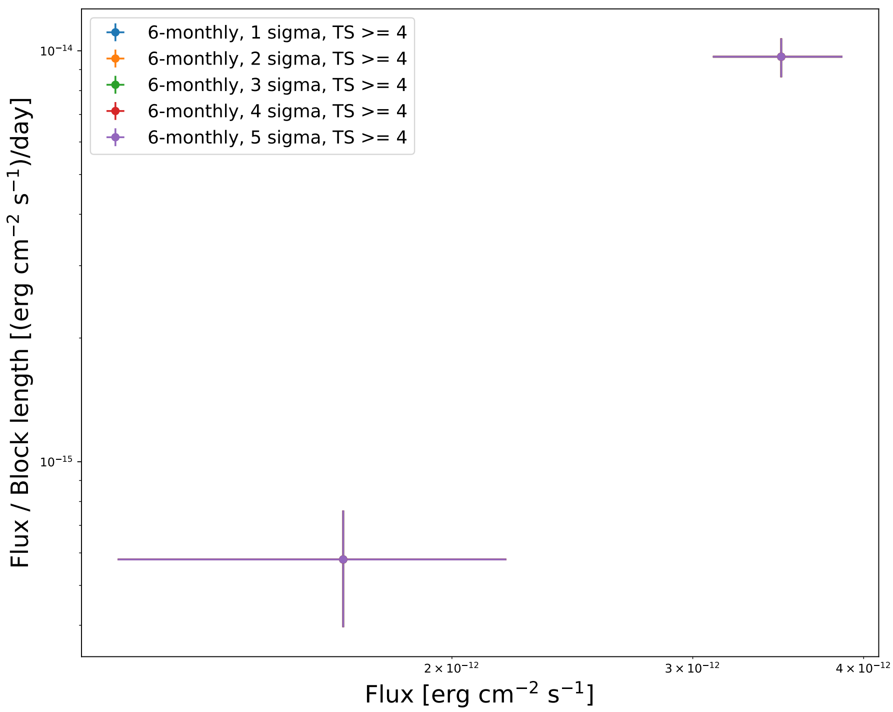

Figure 3: The fluxes and duration of the Bayesian blocks obtained for 1ES 0229+200 VHE band, with monthly binning, with different values for the minimum significance of a change point. The fluxes and duration of the blocks at a 1 sigma level up to 5 sigma are identical.

at different energy ranges. The goal of this work is a broader understanding about the emission scenarios at play in these astrophysical sources. Further improvements depend on the collection of more MWL data combined with the conclusion of the time evolution studies, by analyzing the data at different time periods.

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