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Study of the multi-wavelength properties of extreme gamma-ray blazars

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Among blazars, active galactic nuclei whose relativistic jet is pointing towards us, extremely high synchrotron peaked (EHSP) blazars are the least luminous but most energetic ones, with synchrotron peaks reaching frequencies of $\nu_{\rm sync} > 10^{17}$ Hz. They represent the end of the 'blazar sequence', poorly characterized so far due to limited statistics. The number of known sources of this class is still only a few dozen, yet they are critical to understanding acceleration processes in jets and non-thermal emission mechanisms. In this work, we search for EHSPs within a selection of 657 high-synchrotron-peaked (HSP, $\nu_{\rm sync} > 10^{15}$) blazars and blazar candidates (BCU) from the 2BIGB catalog by studying the broadband spectral energy distribution (SED). We use archival public data from the Space Science Data Center (SSDC) SED Builder service to obtain the multi-wavelength broadband spectral energy distribution of the selected sources, as well as our own analysis of Swift-UVOT and Swift-XRT data to constrain the synchrotron component. After modeling their SEDs, we identify new EHSPs and analyze their structure, physical properties, and possible evolution in the context of the more general population of blazars.

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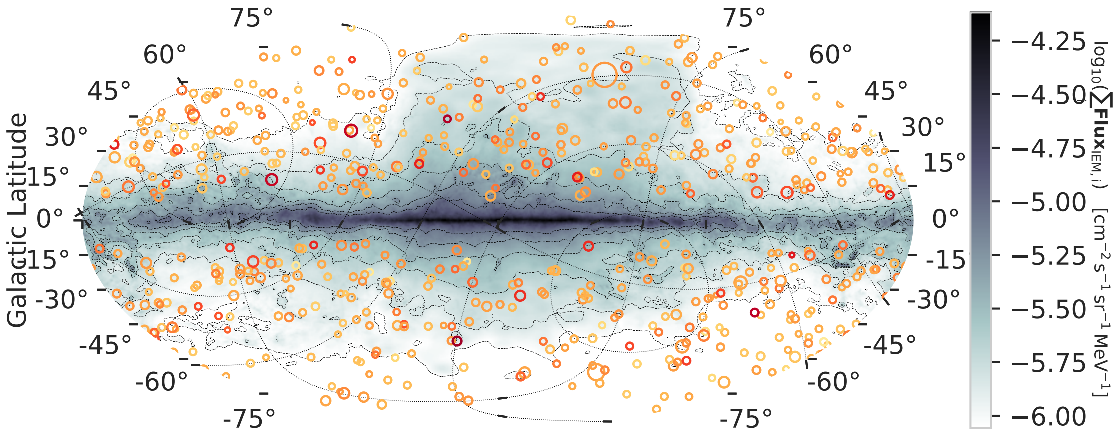


Figure 1: Location of the selected sources (galactic coordinates). Each circle represents a source, with a color that corresponds to their flux (in log-scale, with red tones for brighter sources). The size of the circle is proportional to $1/\sqrt{z}$. For reference, the diffuse γ-ray emission from the Galaxy is shown in blue tones.

1. Introduction

In the unified model of radio-loud active galactic nuclei (AGN), extreme high-synchrotron-peaked (EHSP) blazars stand as a relevant class of sources that challenge theories of particle acceleration and gamma-ray emission in jets. As other blazars, their basic broadband spectral energy distribution has a double-peaked structure, the lower energy region usually attributed to synchrotron emission from relativistic electrons in a shocked plasma and a higher energy component whose origin is disputed. While the precise definition of 'extreme' changes from author to author, and different sub-types have been proposed [1, 2] (hard-TeV, transitional TeV, etc), a common characteristic of all EHSPs is that they are able to accelerate electrons up to energies where the corresponding synchrotron emission peak is found in the X-ray band or beyond.

In [3], we analyzed a limited sample of candidate blazars from the 2BIGB catalog [4], focusing on blazars classified as of unknown type (BCU) in the 4FGL catalog [5]. Using simple selection criteria, 17 good candidates of EHSPs and 5 likely HSP blazars were extracted. In that work, multi-wavelength archival spectral energy distribution data were collected and interpreted using a simple one-zone synchrotron-self-Compton (SSC) model plus thermal components. This analysis technique showed that these sources, as a population, do not strike as very bright sources in the Very High Energy (VHE, E > 100 GeV) band, and do not have particularly hard spectral indices, as previously suggested when focusing on sources with bright VHE emission. Furthermore, they showed rather common model parameter values and, in most cases, were found in rough equipartition between the kinetic energy of the electrons and the magnetic energy density. This contradicted previous studies where a very low-magnetization of their jets, or structured jets, seemed to be required to explain the emission signatures from extreme blazars [6].

This work examines the multi-wavelength properties of EHSPs by considering a larger sample of γ-ray sources from the 2BIGB, with a larger spectral coverage for each of them: γ-ray band from *Fermi*-LAT's 4LAC-DR3 [7] and STeVECat [8] (successor of GammaCat[(‡)]), X-ray and optical data from *Swift*-XRT and *Swift*-UVOT, and archival data provided by the Space Science Data Center

- ASI (§) and ViZier [9].

2. Blazar sample

The base catalog that we used is the 2BIGB catalog [4], a catalog of 1160 γ-ray emitting blazars with infrared properties similar to those of HSPs. With respect to [3], we updated the base *Fermi*-LAT catalogs to 4FGL-DR3 and 4LAC-DR3 and removed most of the cuts, including the requirement of the sources to be classified as Blazar Candidates of Unknown type (BCUs) in the 4FGL catalog. We require each source to have flux measurements available in all bands (optical/UV, X-rays and γ rays), a redshift estimate (even if photometric), and to be outside the galactic plane ($|b| > 10°$). A total of 657 sources passed the cuts, from which 269 are flagged as variable in *Fermi*-LAT and 388 not variable (variability index in 4FGL lower than 18.47). The redshift estimates were obtained from different sources: 4LAC-DR3 itself, from [10] and [11], and from the 2BIGB itself. The distribution of the resulting sources is shown in Figure 1.

3. Multi-wavelength data

For each source, we collect spectral information from the following data streams:

- 4LAC-DR3 / 4FGL-DR3: fluxes for 7 energy bins available in the catalog for each source.
- STeVECat: the Spectral TeV Extragalactic Catalog [8].
- Space Science Data Center - ASI *SED builder* (archival data)
- Vizier (using the python package `astroquery`) (archival data)
- Swift-XRT: using an automatic analysis tool based on the `UKSSDC` XRT-prods python api and performing for each case the hydrogen-column de-absorption of the measured spectra.
- Swift-UVOT: Using an automatic analysis tool built on top of the official HEASARC *uvot-product* package.
- Zwicky Transient Facility (ZTF): Automatic 'forced' photometry(¶) of sources visible from the northern hemisphere using IRSA IPAC. The photometric data is available in two Sloan bands, r and g.

(‡)https://github.com/gammapy/gamma-cat
(§)https://tools.ssdc.asi.it/SED/
(¶)Given the difference images that ZTF produces, the 'forced' photometry is performed on a particular position in the sky, independently of whether there is a triggered alert in that position.

4. Results

4.1 Multi-wavelength variability

Blazars, as a population, are very variable sources, but the exact mechanisms producing it are still unknown. Flux can dramatically change at different time scales, from years-duration increases or decreases in luminosity to brief minute-scale flares. To some extend, the duration of these events correlates with the emission region size due to causality arguments. In some cases, hints of pseudo-periodicity are spotted at different wavelengths which may encode the binary nature of some blazars [12].

The variability of a given blazar can be also wavelength-dependent, particularly if external Compton or multiple emission regions are present, or if hadronic processes (typically slower accelerating particles giving shape to a more slowly evolving emitted flux) or thermal components (e.g. host galaxy emission, not variable) dominate in a given band.

A powerful way to study blazar variability in different bands and different times is the so-called Fractional variability [13], which is the square root of the fractional excess variance. Fractional variability is defined as

$$F_{var} = \sqrt{\frac{S^2 - \langle \sigma_{err}^2 \rangle}{\langle x \rangle}^2} \qquad (1)$$

where $S^2 = \sum_{i=1}^{N}(\langle x \rangle^2 - x_i^2)/(N-1)$ is the sample variance and $\langle \sigma_{err}^2 \rangle = \sum_{i=1}^{N} \sigma_{i,err}^2$ the mean square error.

It is important to note that Fractional variability requires us to have a complete and unbiased sample, covering both high states and low states. This is however not what we usually have, unless operating in Survey mode (e.g. *Fermi*-LAT, ZTF). An additional limitation arises from the number of points being required to compute F_{var}, which relates to the number of 'sources' that survive in the sample for bands with sparse monitoring. In order to not limit dramatically the number of sources, we will require a minimum of 3 points to estimate F_{var}. Even with systematic uncertainties already described, this F_{var} allows us to qualitatively compare the variability for the 356 sources for which we have a F_{var} estimation in all bands (*Fermi*-LAT, *Swift*-XRT and *Swift*-UVOT). A quick look into the histogram of Fractional variability in the different bands is shown in Figure 2. Ignoring for now their uncertainties, we see that our sample of sources has similar distributions of F_{var} for γ rays (*Fermi*-LAT, as extracted from the 4FGL catalog) and X-rays (*Swift*-XRT), larger than the ones in optical and UV (*Swift*-UVOT). Since the exposure (and therefore the completeness) in UVOT is similar to the one in XRT, the data suggest a significantly stronger variability at higher energies, perhaps due to thermal components (low variability) significantly polluting the UVOT data.

4.2 Broadband spectral energy distribution modeling

In the simplest leptonic emission models, blazars radiate through two fundamental processes: (i) synchrotron radiation from ultrarelativistic electrons, which produces a characteristic bump from radio to X-rays, and (ii) inverse Compton scattering of the same electron population with the photons produced in the synchrotron process (synchrotron-self-Compton, SSC) and, if present, any other

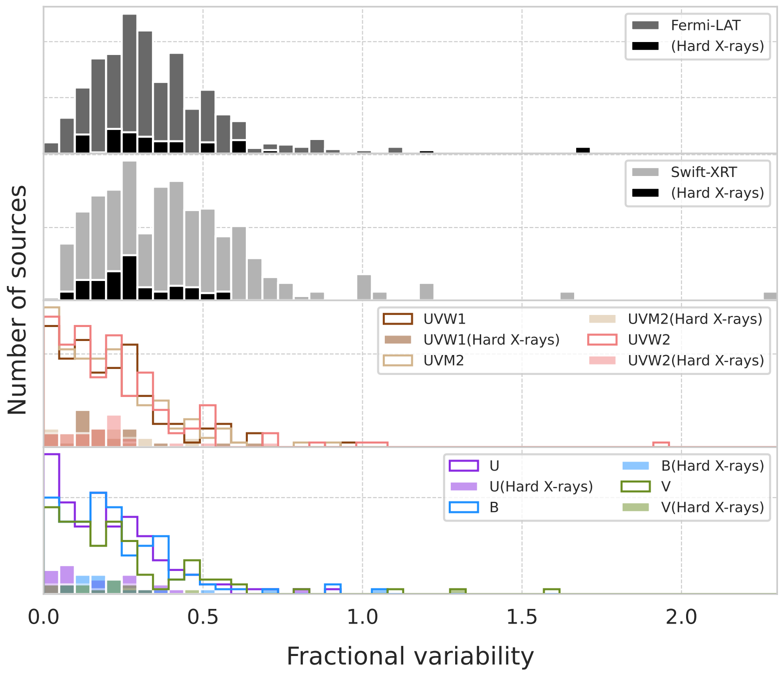
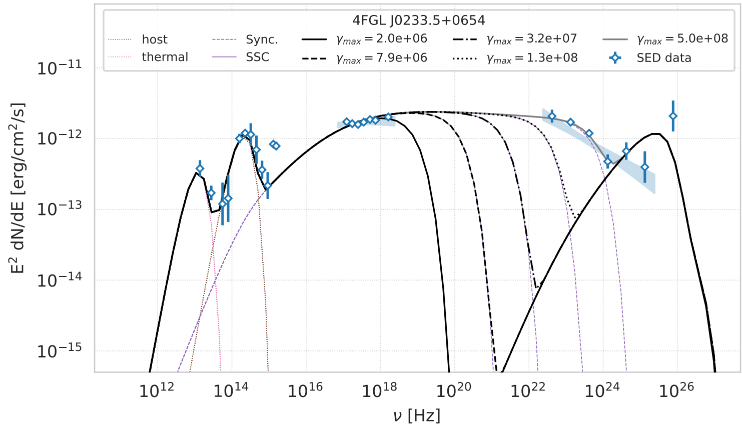


Figure 2: Fractional variability in different bands, for both the full sample with fractional variability measurements in all bands, and the subsample of sources with hard X-ray spectra (index $\Gamma_X < 2$).

significant external radiation field (external Compton, EC). Other components may exist from IR throughout X-rays, mainly due to the host galaxy (usually giant elliptical galaxies with emission predominantly from old stars with a thermal emission characterized by $T_{\rm eff} \sim 2-4\times10^3$ K) and possible elements of the AGN such as the accretion disk, infrared torus ($T_{\rm eff} \sim 10-10^3 K$), and broad and narrow lines from gas clouds moving at different speeds. For extreme blazars, it is common to assume that accretion is weak, SSC dominates, and only the host galaxy emission is locally significant with respect to non-thermal dominated spectrum.

The assumed geometry is key to estimating how much radiation is produced in the jet: structured jets, multiple interacting acceleration regions, or stars crossing the jet would indeed produce a significant inverse Compton scattering of external photon fields. In this sense, HSP and EHSP blazars are often thought to have a relatively simple structure, with weak accretion flows and a relatively weak jet. Therefore, in the absence of strong flaring events, their broadband spectra are often well described by simple one emission zone models [3, 14]. In contrast, sources that present strong and fast variability are often recalled as evidence of small secondary radiation zones developing along the jet. To keep the modeling simple and self-consistent using a simple one-zone SSC scenario, we will focus on the sub-sample of 388 non-variable sources, and further remove sources hinting a strong variability (as in large flux dispersion) in the archival data in optical and X-rays.

The actual implementation of the SED modeling code uses `JetSet` [15, and references therein]. In all cases, we implement an attenuation of the spectra using the extragalactic background light (EBL) model from [16]. We explore two independent methods to extract the best-fit parameters: (i)



R	cm	1.e+16
B	gauss	2.4e-02
theta	deg	2.e+00
BulkFactor		2.e+01
gmin		1.e+04
N	1 / cm3	7.079e+01
gamma_break		1.778e+05
p		1.6e+00
p_1		3.070e+00
T_DT	K	2.e+02
T_Host	K	3.5e+03

Figure 3: SED modeling of 4FGL J0233.5+0654 using a SSC scenario plus a dusty torus (DT) plus a simplification of the host galaxy radiation field using a black-body emitter.

an unbiased fitting using `minuit` [17], where the best-fit parameters are obtained by minimizing the deviation of the estimated broadband spectral energy distribution with respect to the existing multi-wavelength dataset, and (ii) a supervised search for the best parameters, to explore cases where the modeling parameters are particularly extreme. The former allows us to explore the parameter space and get an estimate, not biased toward existing parameter values often found in the bibliography, of where our source sample stands with respect to other blazars. An example of the latter approach is presented in Figure 3, where both the X-ray data from Swift-XRT and the γ-ray spectrum from *Fermi*-LAT seem to indicate that the synchrotron component extends well into the hard X-rays, even to γ rays, preferring very extreme maximum Lorentz factors ($\gamma_{\rm max} \gtrsim 10^8$) over more typical values of $\sim 10^6$, which fail to explain the smooth transition observed in the SED from X-rays to γ rays. It is also interesting to note that, due to EBL, the effect of IC scattering of electrons with Lorentz factors $\gamma \gtrsim 10^6$ is almost negligible in the VHE spectra, being only possible to probe such values using data in the keV–MeV band.

4.3 Energy budget

According to magnetohydrodynamic (MHD) simulations, when jets are launched they are magnetically dominated [18–20], and progressively as the jet develops the magnetic energy density is converted into kinetic energy of the accelerated particles until equipartition (i.e. matter dominated outflow) is reached. Since EHSP blazars are supposedly well-developed jets with only weak accretion flows, we can argue that equipartition is expected to happen.

There are however many claims [1, 2, 6] that for VHE emitting HSP BL Lacs, simple one-zone models fail to reproduce the observed broadband spectrum unless a very weak magnetization of the jet is assumed, implying a kinetically-dominated outflow. Recent studies [3] have suggested that this weak magnetization seems to be required only for sources with significant VHE emission, while non-VHE emitters are in rough equipartition. In this work, we expand significantly the source sample (by a factor 10 in number of sources) with respect to previous studies, while also analyzing all existing X-ray data from *Swift*-XRT and *Swift*-UVOT for the optical/UV, in order to improve the accuracy of the synchrotron component modeling.

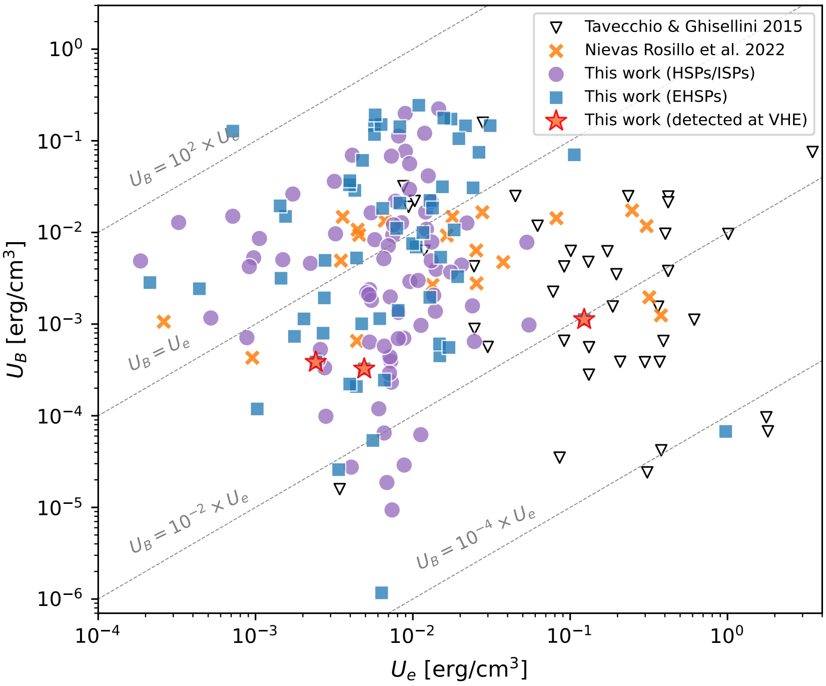


Figure 4: Magnetic energy density as a function of the kinetic energy density of the electrons.

In Figure 4 we show the energy budget of the first 134 spectral modeled sources out of the 388 classified as non-variable in *Fermi*-LAT. Out of them, 60 are classified according to the model as EHSPs ($\nu_{\rm sync,P} > 10^{17}$ Hz) and 74 are either HSPs or ISPs/LSPs ($\nu_{\rm sync,P} < 10^{17}$ Hz). As it can be seen, the two samples are distributed at the same region in the diagram, clustering around the line of $U_B = U_e$, further supporting the conclusions of [3], this is, EHSPs and HSPs are not fundamentally different sources, and simple one-zone SSC models are a good match to explain their multi-wavelength SED, at least when the sources are not variable.

5. Discussion and Conclusions

We have explored the multi-wavelength properties of 657 sources from the 2BIGB, a catalog of blazars detected in the γ-ray band with infrared properties similar to those of HSPs and EHSPs. Out of them, 269 are flagged as variable in *Fermi*-LAT and 388 have a variability index lower than 18.48 (non-significant variability). For the 657 sources, we collected γ-ray data from *Fermi*-LAT and STeVECat, which is a catalog that includes most (if not all) VHE spectra from extragalactic sources published to date, as well as X-ray and optical/UV data systematically analyzed from *Swift*-XRT and *Swift*-UVOT. This work is one of the first systematic studies of multi-wavelength properties of HSP and EHSP blazars to date, including not only spectral information but also their time-resolved emission.

We performed a first analysis of the variability of the full sample through the Fractional variability method in section 4.1. By considering sources with Fractional variability available in all instruments, we observe that the variability is stronger in X-rays and γ rays than in optical and

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UV, a possible indicator of thermal features (less variable) existing in the optical and UV spectra of our sources.

In section 4.2 we present the results of the MWL SED modeling of the first 134 (out of 388) non-variable sources of the sample, with roughly half being EHSPs and the rest HSPs or ISPs/LSPs. We find no indication of significantly different magnetization of the jets of both populations, and conclude that both samples are in rough equipartition (as observed previously by [3]). Only 3 sources in the sample of EHSPs are known VHE emitters.

The complete analysis of this new catalog of multi-wavelength properties of HSP and EHSP blazars will be presented in upcoming publications, focusing on both the variability of the sources and the modeling of their SEDs.

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