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Modelling and fitting of Extreme TeV BL Lacs

Alberto Sciaccaluga,[a,b,*] **Fabrizio Tavecchio**[b] **and Marco Landoni**[b]

[a] *Dipartimento di Fisica, Universita' degli Studi di Genova, Via Dodecaneso 33, Genova, Italy*

[b] *INAF – Osservatorio Astronomico di Brera, via E. Bianchi 46, Merate, Italy*

E-mail: alberto.sciaccaluga@inaf.it

Extreme TeV BL Lacs, a unique class of blazars with distinct spectral and temporal features, cannot be explained by single-zone models that rely on single shock acceleration. To address this, we developed a dual acceleration model where a recollimation shock and downstream turbulence energize non-thermal electrons. To assess the model's robustness, we compared it with data from some Extreme TeV BL Lacs. We chose to automate the parameter space exploration, focusing on understanding the distributions and cross-correlations of these parameters. This automation of parameter space exploration was facilitated by a Markov Chain Monte Carlo (MCMC) sampler, specifically `emcee`. The results showed that the parameter distributions closely align with theoretical predictions. However, the cross-correlation among parameters is complex, leading us to conclude that employing an MCMC sampler for parameter space exploration is crucial in capturing the complexity of time-dependent phenomenological models.

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1. Introduction

Active Galactic Nuclei (AGN) are the most powerful persistent energy sources of the Universe. The class of radio-loud AGNs is defined by the presence of a relativistic jet. They are categorized into various classes based on observational characteristics, which mainly depend on the viewing angle. Blazars are a type of radio-loud AGNs whose jets point almost directly towards the observer [1, 2]. Their emission is dominated by non-thermal jet component, amplified by relativistic Doppler beaming.

Blazars show a Spectral Energy Distribution (SED) featuring two prominent humps. The first hump is attributed to synchrotron emission from non-thermal electrons, while the second hump's origin is debated. It might arise from non-thermal electrons interacting with synchrotron photons or ambient photons (Synchrotron Self Compton or external Compton models) or from hadronic processes like proton synchrotron emission or photo-pion production [3, 4].

Blazars are further classified based on the peak frequencies of these humps [5]. The Extremely High-frequency-peaked BL Lacs (EHBL) are the most efficient accelerators. They can be divided into two further sub-classes: Extreme Synchrotron BL Lacs (with the first peak above 1 keV) and Extreme TeV BL Lacs, which presents in addition the second peak above 1 TeV and a hard GeV spectrum (characterized by $\Gamma < 2$ where $F_\nu/\nu \propto \nu^{-\Gamma}$). Moreover, Extreme TeV BL Lacs show low temporal variability at high energies, a rarity among blazars [6, 7].

Explaining the SEDs of these sources challenges the conventional leptonic single-zone model with single shock acceleration. The spectral traits suggest a high minimum Lorentz factor, a small magnetic field far from equipartition, and a power-law index ($p < 2$ where $dN/dE \propto E^{-p}$) inconsistent with diffusive shock acceleration theory. Various hypotheses have been proposed, including Maxwellian-like electron distribution [8], a beam of high-energy hadrons [9], internal absorption [10], large-scale jet emission [11], lepto-hadronic models [12], and multiple shock acceleration [13].

To account for the peculiarities of Extreme TeV BL Lacs, we developed a double acceleration mechanism, considering the low magnetization likely for these sources. After the acceleration by a recollimation shock, non-thermal particles are further energized by the turbulence developed downstream, via resonant interaction. Considering the balance between turbulence cascading and damping, it is clear that turbulence is heavily damped, an aspect that cannot be ignored [14]. Therefore, we formulated a time-dependent leptonic one-zone model where we included turbulence damping. It begins with calculating non-thermal electron and turbulence spectra, followed by emission modeling using the Synchrotron Self-Compton model. Our model was initially adjusted on the data from the prototypical Extreme TeV BL Lac 1ES 0229+200 by visual inspection [15].

We extend our model to include other sources (for more information, see [16]), employing a Markov Chain Monte Carlo (MCMC) sampler to automate and parallelize the comparison between model predictions and observational data.

2. MCMC

In our previous work, the model was manually adjusted to fit the data, a common practice in literature. However, this method has several drawbacks, including confirmation bias and the need for individual adjustments for each source. To address these issues, we moved to Markov Chain Monte Carlo (MCMC) sampling. This approach offers multiple benefits: it automates the fitting process, allows for the determination of parameter distributions and their cross-correlation, and enables the application of non-diagonal priors, i.e. priors that depend on multiple parameters.

Our model includes various parameters: the emission region radius (R), plasma Alfven velocity (v_a), total magnetic field (B), and the electron and turbulence injection power in the jet frame, denoted respectively as P_n and P_w, along with the relativistic Doppler factor (δ). We set $\delta = 20$ as a constant because, if left unconstrained, it tends to reach unrealistically high values ($\delta \sim 100$), which are unplausible. On the contrary, a very low value for δ would imply an unrealistically large emission region, inconsistent with the expected blazar emission region size (sub-pc scale). This fixed value is smaller than usually employed in leptonic one-zone models, leaving us with five parameters.

We used the Python library `emcee` for MCMC sampling. We adopted a Gaussian Likelihood, and while it is standard to include a term for accounting for the non-simultaneity of the data, tests incorporating this factor resulted in negligible values, due to the low temporal variability of the considered sources, so we excluded it.

Logflat priors were applied to all parameters, with broad ranges to explore the parameter space. We imposed two non-diagonal priors. The first ensures that turbulence does not dominate the ordered field in the emission zone, and the second reflects that the non-thermal component is a minor part of the total post-shock plasma. These constraints are on the ratios of the energy density of magnetic turbulence to the total field, and the number density of non-thermal electrons (n_e) to thermal plasma (n_p), calculated from Alfven velocity and the average magnetic field: respectively $\delta B^2/B^2 < 0.1$ and $n_e/n_p < 0.1$.

3. Results

As representative example of our work we show the results obtained with the prototypical Extreme TeV BL Lacs 1ES0229+200. We initialized 30 walkers, each moving for 10000 steps and with $\sim$ 1000 burn-in steps. In Fig. 1 the flux points are shown together with the 1σ uncertainty and median of SEDs obtained from the posteriors drawing $\sim$ 1000 random samples.

The model uncertainty in the x-ray band is lower compared to for higher energy bands, as the measurements from Swift and NuSTAR are more accurate than those from Fermi and VERITAS. The FERMI spectrum is accurately reproduced due to the softening caused by turbulence damping. The Very High Energy (VHE) data are generally consistent within a 1σ uncertainty range, expect for the highest energy flux points, yet still within a $< 2\sigma$ range.

The corner plot, see Fig. 2, shows narrow distributions in logarithmic space, but strongly not-gaussian. Furthermore, the parameters exhibit a strong correlation, an effect that is difficult to discern through visual comparison between the model and the data.

4. Conclusions

The data of 1ES 0229+200 are well reproduced by the double acceleration model, as already found via visual inspection. MCMC sampling is an improvement, because it showed the distribu-

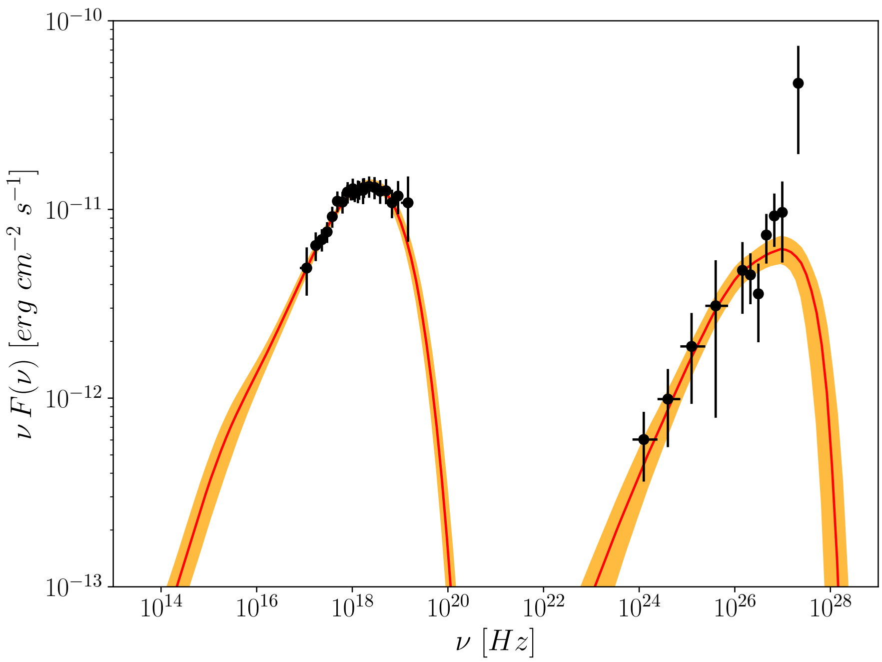

Figure 1: Flux points with their errors (black) of 1ES 0229+200 with 1σ uncertainty (orange) and median (red) obtained from the model posterior

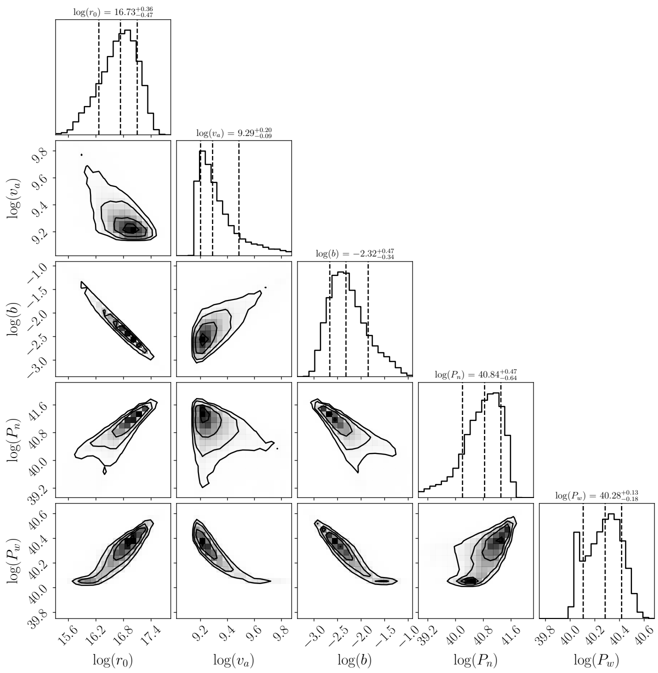

Figure 2: Corner plot of 1ES 0229+200

tions of the several parameters and more importantly their cross-correlations. We conclude that MCMC sampling is necessary to understand the full complexity of the model. This will be further investigated in a paper in preparation.

The relativistic Doppler factor needed by the model excludes that the post-shock region is disrupted by global instabilities [17, 18]. A different scenario must be invoked, where turbulence forms after the recollimation shock, but without prevailing.

Recent measurements from Imaging X-ray Polarimetry Explorer (IXPE) revealed that Extreme TeV BL Lacs have a high x-ray polarization, larger than optical [19], which is hard to reproduce with our simplified model. More complex modeling is necessary though, therefore one of our next step is to calculate jet emission, polarization etc. starting directly from MHD simulations, via the Lagrangian particles technique [20].

The next generation of high energy facilities, such as ASTRI and CTA, will collect more constraining data, improving the parameter uncertainties. Moreover, if the double acceleration model is correct, these instruments will observe the cut-off above 10 TeV, which will exclude Extreme TeV BL Lacs from the sources exploitable to study phenomena beyond the Standard Model, such as axions and Lorentz Invariance Violaton (LIV).

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