Photohadronic origin of multi-TeV flarings from high energy peaked blazars

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Abstract

VHE flaring events have been observed to be a predominant event of the activity of high energy peaked blazars (HBLs). These flaring epochs involve energies in the GeV-TeV range and different timescales, yet their emission mechanisms are still not well understood. The emitted γ-rays en route to Earth undergo energy-dependent attenuation due to the interaction with extragalactic background light. Considering the photohadronic model where Fermi-accelerated protons interact with the seed photons in a double jet scenario, we derived a simple relation for the observed multi-TeV γ-ray flux as a function of two free parameters. We studied 42 flaring epochs from 23 HBLs and found that our model accurately describes the observed VHE spectra for all these cases, supporting the photohadronic origin of multi-TeV γ-rays. Moreover, this model allows to constrain the power spectrum of seed photons during the flaring period even if the simultaneous spectral energy distribution is unknown. We also used this model to set stringent bounds on the redshifts of two HBLs with unknown distances but observed multi-TeV spectra.

1 Introduction

Blazars are a subclass of active galactic nuclei (AGNs) characterized by a non-thermal emission that spans across all the electromagnetic spectrum, with a flux variability that ranges from minutes to days [1]. They stand out in observations due to the fact that their jets are point or closely pointed towards Earth, which is responsible for their very high luminosity and the relativistic beaming of energy [2]. Blazars possess a spectral energy distribution (SED) characterized by two peaks in its flux. The first peak, in the IR to X-ray range, is produced by the synchrotron emission of relativistic electrons accelerated in the jet. The second peak, in the X-ray to γ-ray range, is generally understood to be the result of the scattering of high energy electrons with the self-produced synchrotron photons in the jet (Self-Synchrotron Compton, SSC) [3, 4] or from external nearby sources such as photons from the accretion risk, broad line regions, or the dusty torus (External Compton, EC) [5, 6]. Leptonic models have been widely successful in explaining the multiwavelength emission from blazars [7, 8]. Depending on the location of these two peaks in the energy range, blazars are classified as: flat-spectrum radio quasars (FSRQs), low energy peaked blazars (LBLs), intermediate energy peaked blazars (IBLs), high energy peaked blazars (HBLs), and extreme high energy peaked blazars (extreme HBLs) [9]. Other classification schemes have also been proposed.

Flaring events in GeV-TeV energies seem to be a predominant component of the activity of blazars [10]. Mrk 421 was the first and nearest HBL to be detected in TeV energies by the Whipple telescopes [11], and other Imaging Atmospheric Cherenkov Telescopes (IACTs) such as VERITAS and MAGIC have been successful in observing several more blazars such as Mrk 501 and 1ES 0229+200 in the very high energy (VHE) range [12, 13]. Flarings have been observed to be unpredictable and to oscillate rapidly between active and quiescent states for different timescales [10]. In many cases, a strong temporal correlation between X-rays and multi-TeV γ-rays has been observed, as predicted by the standard one-zone leptonic models. However, the detection of multi-TeV γ-rays without simultaneous X-ray counterpart during other flarings (orphan flarings) is difficult to explain in the previous scenario [14, 15]. Two-zone leptonic models as well as hadronic and hybrid ones have been developed to explain these observations [8, 16–18]. Multiple multi-wavelength campaigns have been performed to reconstruct the SED of these flarings in order to constrain these theoretical models [10, 19].

In the following work, we analyze the reconstructed VHE γ-ray spectra of 42 flaring events from 23 HBLs and use the photohadronic model to describe the observations.

2 Photohadronic model

In the photohadronic scenario, the observed VHE γ-ray emission is predominantly accounted by the decay of neutral pions produced from a pγ interaction [20, 21]. In this scenario, Fermi-accelerated protons interact with the background seed photons in the jet to produce a Δ resonance ($\sigma_\Delta = 5 \times 10^{-28}\mathrm{cm}^{-2}$), which subsequently decays as,

$$p + \gamma \to \Delta \to \begin{cases} p\pi^0 & \text{(fraction } 2/3) \\ n\pi^+ & \text{(fraction } 1/3) \end{cases} \tag{2.1}$$

where 2/3 and 1/3 are the branching ratios. The neutral and charged pions subsequently decay into γ-rays and neutrinos, i.e., $\pi^0 \to \gamma\gamma$ and $\pi^+ \to e^+\nu_e\nu_\mu\bar{\nu_\mu}$. The kinematical condition for the above process is given by [21],

$$E_\gamma \epsilon_\gamma = \frac{0.032\Gamma\Delta}{(1+z)^2} GeV^2 \tag{2.2}$$

where Γ, Δ, and z are the bulk Lorentz factor, Doppler factor, and redshift, respectively. E_γ and ϵ_γ are the γ-ray and seed photon energy in the observer's frame, respectively.

The photohadronic model relies on the standard leptonic interpretation for the origin of the synchrotron and SSC peaks in blazars, in particular for HBLs [21]. The flaring is assumed to occur within a compact and confined volume of size R'_f inside a blob of radius R'_b (where the prime denotes the jet co-moving frame). In a canonical jet scenario, the production of Δ resonance is low due to low photon density in the jet, and thus super-Eddington power for the proton must be invoked [22]. To avoid this scenario, a double-jet structure for the HBL is proposed: a compact, inner jet of high photon density ($n_{\gamma,f}$) is enclosed by an outer jet of lower photon density (n_γ). The inner and outer jet move with almost the same bulk Lorentz factor as the blob $\Gamma_{in} \approx \Gamma_{out} \approx \Gamma$. The geometry of this structure is shown in Fig. 1 of [21]. In HBLs, it is generally observed that $\mathcal{D} \approx \Gamma$. This composite structure is supported by simulation of similar models [23].

The stability of the jet on large scales during the flaring epoch can be estimated from the ratio σ of the magnetic stress and the kinetic stress. Considering the typical values in HBLs for the magnetic field $B \sim 1\mathrm{G}$, proton density $n_p \sim 10^{-1} - 10^{-2}\mathrm{cm}^{-3}$, and bulk Lorentz factor $\Gamma \sim 10$, we get $\sigma \sim 0.4$ which corresponds to a stable inner jet [ref]. The inner photon density is constrained by comparing the jet expansion timescale t'_d with the $p\gamma$ interaction timescale $t'_{p\gamma}$ and by taking into account that the high energy proton luminosity must be smaller than the Eddington luminosity [18].

The produced VHE γ-rays can in principle interact with the background low-energy photons in the jet through electron-positron pair production ($\gamma\gamma \to e^+e^-$). Nevertheless, it has been observed that the jet medium is transparent to this attenuation where the optical depth ($\tau_{\gamma\gamma}$) is small [24]. However, propagating γ-rays en route to Earth are known to undergo energy-dependent attenuation via the same process through the interaction with extragalactic background light (EBL) [19, 25, 26]. This attenuation significantly modifies the shape of the VHE spectrum and therefore a proper modeling of the EBL SED is fundamental to understand the observed multi-TeV emission. Well-known models are widely used in the description of these VHE phenomena [19, 26].

To reconstruct the observed VHE γ-ray flux F_γ, we observe that it must be proportional to the proton fluxas well as the background seed photon inner density, that is, $F_\gamma \propto F_p n'_{\gamma,f} \propto E_p^2 \frac{dN}{dE_p} n'_{\gamma,f}$. Fermi-accelerated protons have a well known power-law spectrum, $F_p \propto E_p^{-\alpha+2}$, where α is the proton spectral index and $\alpha \geq 2.0$ [27]. Due to adiabatic expansion of the inner jet, its photon density decreases as it crosses into the outer jet. As the inner photon density cannot be directly known a priori, a scaling behavior is assumed between the photon densities of the inner and outer regions, i.e., they have the same slope [21]. As the outer photon density is known to be inversely proportional to the seed photon energy ϵ_γ and proportional to its flux $\Phi(\epsilon_\gamma)$, and using the scaling behavior 2.2, we can express the inner photon density as $n'_{\gamma,f} \propto \Phi(\epsilon_\gamma)\epsilon_\gamma$.

Combining the previous assumptions and taking into account the EBL attenuation, the observed flux is given by,

$$F_\gamma(E_\gamma) = A_\gamma \Phi_{SSC}(\epsilon_\gamma) \left(\frac{E_\gamma}{TeV}\right)^{-\alpha+3} e^{-\tau_{\gamma\gamma}(E_\gamma,z)} \tag{2.3}$$

where A_γ is proportionality constant. The photohadronic model has been previously used to describe the flaring events of several HBLs [20, 21, 28]. In all cases, it has been observed that ϵ_γ always falls in the tail region of the SSC SED, which is not observed due to technical limitations. However, leptonic models have predicted that this tail region is a perfect power-law given by $\Phi_{SSC} \propto \epsilon_\beta$, or using 2.2, $\Phi_{SSC} \propto E_\gamma^{-\beta}$, where β is the seed photon spectral index. Substituting this in 2.3, we arrive at a very straightforward relation for the observed VHE γ-ray flux,

$$F_\gamma(E_\gamma) = F_\gamma^{int} e^{-\tau_{\gamma\gamma}(E_\gamma,z)} = F_0 \left(\frac{E_\gamma}{TeV}\right)^{-\delta+3} e^{-\tau_{\gamma\gamma}(E_\gamma,z)} \tag{2.4}$$

where F_0 is a proportionality factor fixed from the observed VHE spectrum and $\delta = \alpha + \beta$ is the spectral index of the photohadronic model. Here, it is not necessary to know a priori the value of β and thus this model is independent of simultaneous SED modelling. Furthermore, the intrinsic flux follows a single power-law characterized by δ, while the differential intrinsic flux spectral index is $\delta_{int} = -\delta + 1$.

3 Multi-TeV flarings

We extracted the data of 42 flaring epochs of 23 HBLs of different redshifts and applied equation 2.4 to describe their observed VHE spectra. We fitted F_0 and δ using a standard minimization of

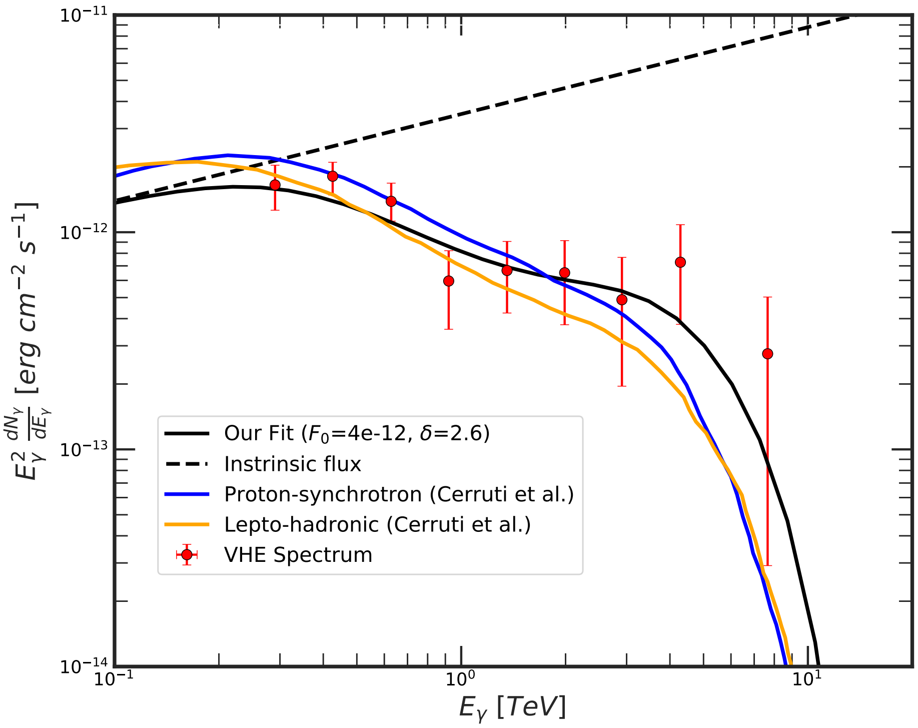

Figure 1: **Multi-TeV SED of 1ES 0229+200**. The VHE spectrum (red points) of 1ES 0229+200 corresponding to the flaring reported between October 2009 and January 2013 [13]. The best fit for the photohadronic model is obtained for $\delta = 2.6$, $F_0 = 3.5 \times 10^{-12}$ erg cm^{-2} s^{-1}. For comparison the proton-synchrotron and lepto-hadronic models of Cerruti et al. [17] are shown.

the cost function and found that the photohadronic model explains very well all these observations with the spectral index δ in the range $2.5 \leq \delta \leq 3.0$. Depending on the value of δ and by comparing with the VHE observations, we were able to roughly classify the flarings into three different states: (i) low state, with $\delta = 3.0$, (ii) high states, with $2.6 < \delta < 3.0$, and (iii) very high state, with $2.5 \leq \delta \leq 2.6$. As we know that $\alpha \geq 2.0$, this constrains the seed photon spectral index β for simultaneous multiwavelength observations in the range $0.0 \leq \beta \leq 1.0$. We briefly adress two of these flaring episodes and compare it with other current theoretical models. The rest of our results are presented in Table 1. For the EBL correction we consider the model of Franchescini et al. [26].

3.1 1ES 0229+200

1ES 0229+200 is a HBL located at $z = 0.1396$ discovered in the Einstein IPC Slew Survey of 1992 [29]. It was observed by VERITAS telescopes during a long-term observation campaign between October 2009 and January 2013, for a total exposure time of 54.3 hours [13]. The observed VHE observations were reported in an energy range 0.29 TeV $\leq E_\gamma \leq$ 7.6 TeV. Cerruti et al. [17] explained the observed multiwavelength SED using both a proton-synchrotron and leptohadronic scenario, where the dominant emission in the last one comes from secondary particles product of $p\gamma$ interactions. However, this model uses 19 parameters to fit the entire SED, which limits its predictive power, and the proton-synchrotron scenario requires magnetic fields in the range

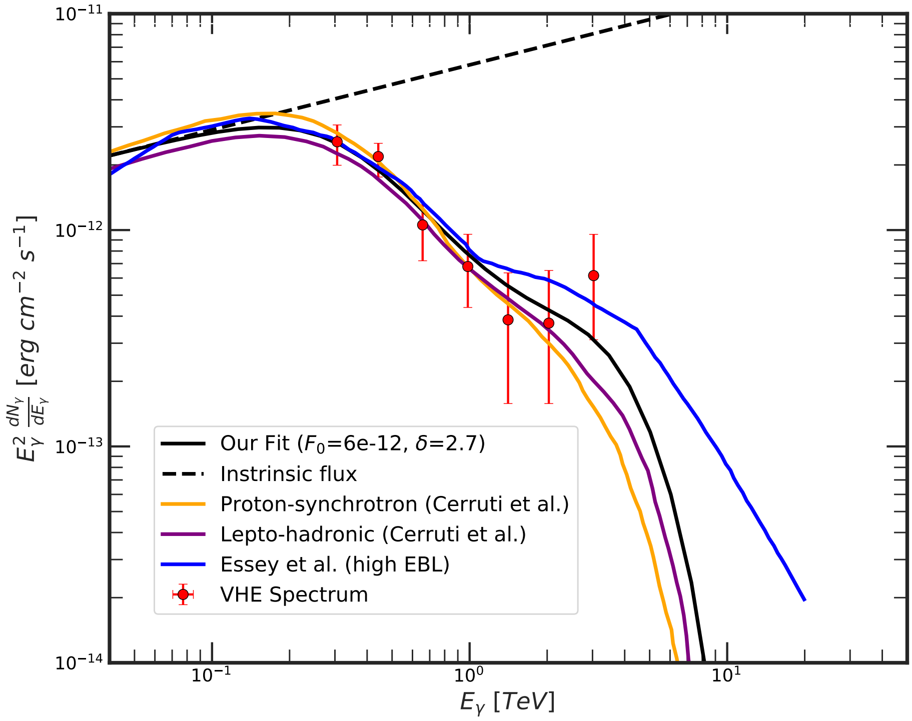

Figure 2: **Multi-TeV SED of 1ES 0347-121**. The VHE spectrum (red points) of 1ES 0347-121 corresponding to the flaring reported between October 2009 and January 2013 [30]. The best fit for the photohadronic model is obtained for $\delta = 2.7$, $F_0 = 6.0 \times 10^{-12}$ erg cm^{-2} s^{-1}. For comparison the proton-synchrotron and lepto-hadronic models of Cerruti et al. [17] are also shown, as well as the hadronic model of Essey et al. [16].

$1 - 160$ G. Using the photohadronic model, we described the observed VHE spectrum with $\delta = 2.6$ and $F_0 = 3.5 \times 10^{-12}$ erg cm^{-2} s^{-1}, which corresponds to a very high emission state. As the photohadronic model only has two free parameters, it greatly improves its predictive capability and understanding. The intrinsic flux follows $F_{\gamma}^{int} \propto E_{\gamma}^{0.4}$. Similarly, the differential spectrum follows $(dN_{\gamma}/dE_{\gamma})_{int} \propto E_{\gamma}^{-1.6}$ which shows that this spectrum is not hard. Both our model and the one of Cerruti et al. are shown in Figure 1. We see that they are very similar below 2 TeV and slightly differ afterwards.

3.2 1ES 0347-121

1ES 0347-121 is a HBL with a redshift $z = 0.188$. It was observed by HESS telescopes between August and December 2006 for a total exposure time of 25.4 hours [30], and was detected in VHE γ-rays in the energy range 0.25 TeV $\leq E_{\gamma} \leq 3$ TeV. Essey et al. [16] explained this flaring and two others (1ES 0229+200 and 1ES 1101-232) using a hadronic scenario, where ultra high energy protons escaping from the jet produce secondary VHE γ-rays by interacting with the cosmic microwave background (CMB) and/or EBL. This scenario requires protons in the energy range $10^8 - 10^{10}$ GeV, which are difficult to produce in the jet environment of the HBL, as well as weak extragalactic magnetic fields ($10^{-17} - 10^{-14}$ G). Cerruti et al. [17] also applied a proton-synchrotron model (with a magnetic field of $1-296$ G) as well as 19-parameter leptohadronic model to explain the same VHE spectrum. Using the photohadronic model, we found that the VHE spectrum is best fitted for $\delta = 2.7$ and $F_0 = 6.0 \times 10^{-12}$ erg cm^{-2} s^{-1}, which corresponds to a high state. This corresponds to an intrinsic flux $F_\gamma^{int} \propto E_\gamma^{0.3}$. As the γ-ray carries 10% of the proton energy, the maximum photon energy of 3 TeV corresponds to a 30 TeV proton energy which is easily produced in the HBL jet. We show our model along with the one of Cerruti et al. and Essey et al. in Figure 2. Below 1 TeV we observe that all have similar behaviors.

4 Other flarings

We show in Table 1 the results for the rest of the flaring events of different HBLs for our photohadronic modeling. From a statistical point of view, 48% of these states are low, 38% are high, and 14% are very high, implying that low and high states constitute the major type of flarings in HBLs. A more exhaustive presentation as well as a detailed list of references for each flaring epoch has been published in [28].

5 Discussions

HBLs are important sources of VHE γ-rays and are known to undergo flaring events at different time-scales and fluxes. Their emission mechanisms at these energies are still highly debated, with leptonic, hadronic, and hybrid models being proposed as potential explanations. Most of these models are characterized for having a large parameter space which limits their predictability power, and those with less parameters usually face difficulties such as having large magnetic fields or invoking super-Eddington luminosity. Moreover, the propagating VHE γ-rays suffer energy-depending attenuation on their way to Earth due to the effect of EBL.

In this work we propose a photohadronic scenario by considering that Fermi-accelerated protons interact with the seed background photons of an inner jet with high photon density, producing a Δ resonance which subsequently decays into γ-rays and neutrinos via intermediate π^0 and π^+ particles, respectively. Based on previous works regarding the shape of the SSC SED and considering the EBL model from Franceschini et al., we were able to derive a simple power-law for the observed VHE γ-ray flux which only depends on two free parameters, a proportionality constant F_0 and the spectral index δ. We applied this relation to study 42 flaring events from 23 HBLs and found that it accurately describes their observed VHE spectra, from which we presented here 7 of these flarings. According to our analysis, the spectral index is roughly constrained in the range $2.5 \leq \delta \leq 3.0$, and depending on the value of δ the state can be classified into low, high, and very high state.

It is important to note that the photohadronic scenario has only been observed to be valid for energies $E_\gamma \geq 100$ GeV, as other contributions may come into play at lower energies, e.g., contributions of leptonic origin. Furthermore, in some cases the averaging of long-term VHE observations is difficult to explain likely due to the averaging of many unobserved short flarings with low emission periods that contaminate the data, as well as the mentioned contribution of leptonic processes in the low energy regime.

Finally, it is worth mentioning that since the proton spectral index $\alpha \geq 2.0$, this models allows to constrain the seed photon index β without a priori knowledge of the simultaneous SED, which has so far been a limitation in the accurate description of the observed VHE spectra in some SSC models. Moreover, the photohadronic scenario only relies on the assumption about the shape of the tail of the SSC SED and the scaling behavior, both of which are reasonable in the jet environment during the flaring epoch. Henceforth, the photohadronic model is a very powerful candidate in describing the origin of multi-TeV γ-ray emission from HBLs.

Name	Redshift(z)	Period	$F_{0,11}$	δ	State
Mrk 421	0.031	2004	51.3	2.95	High
		22 Apr 2006	5.2	2.95	High
		24 Apr 2006	10.7	3.0	Low
		25 Apr 2006	6.9	2.95	High
		26 Apr 2006	5.2	3.0	Low
		27 Apr 2006	16	2.95	High
		28 Apr 2006	5.0	3.0	Low
		29 Apr 2006	4.9	3.0	Low
		30 Apr 2006	13.5	2.5	Very High
		16 Feb 2010	12	3.0	Low
		17 Feb 2010	1.5	3.0	Low
		10 Mar 2010	21	2.6	Very High
		10 Mar 2010	16.5	3.0	Low
		28 Dec 2010	6.7	3.00	Low
Mrk 501	0.034	22 - 27 May 2012	6.3	2.9	High
		23 - 24 Jun 2014	28	2.93	High
1ES 2344+514	0.044	4 Oct 2007 - 11 Jan 2008	0.8	3.0	Low
1ES 1959+650	0.048	May 2002	12	3.0	Low
		Nov 2007 - Oct 2013	2.2	3.0	Low
		21-27 May 2006	1.1	3.0	Low
		20 May 2012	80	2.9	High
1ES 1727+502	0.055	1-7 May 2013	0.9	3.0	Low
1ES 1312-423	0.105	Apr 2004 - Jul 2010	0.20	3.0	Low
B32247+381	0.119	30 Sep - 30 Oct 2010	0.17	3.0	Low
RGB J0710+591	0.125	Dec 2008 - Mar 2009	0.5	2.9	High
1ES 1215+303	0.131	Jan - Feb 2011	90	3.0	Low
1ES 0806+524	0.138	Jan - Mar 2011	1.2	2.9	High
1RXS J101015.9-311909	0.14	Aug 2008 - Jan 2011	0.2	2.8	High
1ES 0229+200	0.14	2005 - 2006	0.4	2.5	Very High
H 2356-309	0.165	Jun - Dec 2004	0.3	2.9	High
1ES 1218+304	0.182	Dec 2008 - 2013	1.5	2.9	High
1ES 1101+232	0.186	2004 - 2005	0.60	2.75	High
1ES 1011+496	0.212	6 Feb - 7 Mar 2014	8.2	3.0	Low
1ES 0414+009	0.287	Aug 2008 - Feb 2011	0.70	2.9	High
PG 1553+113	0.50	26 - 27 Apr 2012	48	2.5	Very High
RGB J0152+017	0.80	30 Oct - 14 Nov 2007	0.3	3.0	Low
HESS J1943+213	$0.14 \leq z \leq 0.19$	May - Jun 2014, Apr - Nov 2015	0.69	2.8	High
PKS 1440-389	$0.14 \leq z \leq 0.24$	29 Feb - 27 May 2012	0.90	3.0	Low
RGB J2243+203	$0.75 \leq z \leq 1.1$	21 - 24 Dec 2014	0.28	2.6	Very High

Table 1: The results of photohadronic modeling for the modeling of additional HBL flaring events are shown. The normalization factor (4th column) is expressed in units $F_{0,11} = 1.0 \times 10^{-11}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$.

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