A Two-zone Photohadronic Scenario for EHBL-like Behavior of Mrk 501

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Abstract

Major outbursts have been observed from the well known high-energy-peaked blazar Markarian 501 since its discovery in 1996. Two episodes of very-high-energy gamma-ray flaring events during 2005 May–July and 2012 June are of special significance, as the source exhibited extreme HBL-like behavior. The successful standard phot hadronic model does not adequately explain these extraneous behaviors. We propose a two-zone phot hadronic scenario to overcome this problem. In this picture, the low-energy regime (zone-1) of the spectrum follows the standard phot hadronic interpretation, while the high-energy regime (zone-2) of the spectrum is new, with a spectral index $\delta_2 \geq 3.1$, which is solely due to the extreme nature of the flaring event. We also estimate the bulk Lorentz factor corresponding to these extreme flaring events. By analyzing many flaring events before and after these extreme events we argue that the extreme HBL-like events are transient and may repeat in the future.

Unified Astronomy Thesaurus concepts: High energy astrophysics (739); Blazars (164); Gamma-rays (637); BL Lacertae objects (158)

1. Introduction

Blazars are a subclass of active galactic nuclei (AGNs) exhibiting very rapid flux variability over the entire electromagnetic spectrum from radio to very-high-energy (VHE, above 100 GeV) $\gamma$-rays (Acciari et al. 2011). The electromagnetic spectrum is produced in a highly relativistic jet pointing toward the observer’s line of sight (Urry & Padovani 1995). The small viewing angle is responsible for the strong relativistic effects, e.g., boosting of the emitted power and shortening of the timescale (Abdo et al. 2010).

Blazars have a spectral energy distribution (SED) characterized by two nonthermal peaks (Dermer & Schlickeiser 1993). The first peak, between infrared to X-ray energy, is produced by the synchrotron emission from a population of relativistic electrons in the jet. The second peak, from X-rays to $\gamma$-rays, is believed to be produced either from the synchrotron self-Compton (SSC) scattering of high-energy electrons with the low-energy self-produced synchrotron photons in the jet (Maraschi et al. 1992; Murase et al. 2012; Gao et al. 2013) or from the external Compton scattering (EC) with external sources such as photons from the accretion disk or broad-line regions (leptonic models; Sikora et al. 1994; Blażejowski et al. 2000).

BL Lac objects can be further classified depending on the frequency of the synchrotron peak as follows: low-energy-peaked blazars (LBLs, $\nu_{\text{peak}} < 10^{14}$ Hz), intermediate-energy-peaked blazars (IBLs, $\nu_{\text{peak}}$ between $10^{14}$ Hz and $10^{15}$ Hz), and high-energy-peaked blazars (HBLS, $\nu_{\text{peak}}$ between $10^{15}$ and $10^{17}$ Hz; Abdo et al. 2010). A new subclass is proposed (Costamante et al. 2001) with extreme spectral properties and energy shifted toward the edge of the blazar sequence. This is called an extreme high-energy-peaked blazar (EHBL). Its synchrotron peak is shifted toward the higher energies ($>10^{17}$ Hz) with respect to conventional HBLs. EHBLs are characterized by low luminosity and limited variability and are difficult to detect with the current gamma-ray surveys. Up to now, only a few EHBLs have been detected at TeV energy and some well known objects are 1ES 0229+200, 1ES 0347-232, RGB J0710+591, and 1ES 1101-232 (Costamante et al. 2018). Among them, 1ES 0229+200 has the highest high-energy peak frequency. Apart from the above EHBLs, two nearby HBLs, Markarian 501 (Mrk 501) and 1ES 1959+650, also have EHBL-like behavior with harder TeV spectra and shifted synchrotron peaks during some flaring episodes (Ahnen et al. 2018; Acciari et al. 2020). Also, as discussed by Foffano et al. (2019), the EHBL class might be a complex population of sources, characterized by different spectral properties and these different behaviors at VHE gamma-rays might characterize different subclasses within the EHBL class.

It is challenging to theoretically explain the shift of the second peak toward higher energy and with a hard spectrum in terms of the standard one-zone leptonic SSC model, as it predicts a softer SSC spectrum in the Klein–Nishina regime, contrary to observations (Paggi et al. 2009). However, these enigmatic spectra can still be explained using the leptonic model at the price of introducing unrealistically large model parameters, such as the values of minimum electron Lorentz factor and bulk Lorentz factor (Ahnen et al. 2018; Acciari et al. 2020). It also needs a very low magnetic field. Several other solutions have been proposed, such as a two-zone leptonic model, IC scattering of the electron with the cosmic microwave background, a spine-layer structured jet model, and variants of the hadronic model (Böttcher et al. 2008; Ahnen et al. 2018; Acciari et al. 2019).

VHE $\gamma$-rays from astrophysical sources are known to undergo energy-dependent attenuation by interacting with the extragalactic background light (EBL) via electron–positron pair...
production (Ackermann et al. 2012). This attenuation affects the shape of the spectrum at very high energies and several models account for this attenuation at different redshifts (Franceschini et al. 2008; Domínguez et al. 2011). As EBLBs are an emerging class of BL Lac objects with extreme spectral properties, particularly in the TeV range, they are an ideal probe for EBL (Tavecchio 2014; Tavecchio & Bonnoli 2015). Moreover, the association of IceCube neutrino event(s) with blazar(s) (Padovani et al. 2016; Aartsen et al. 2018a, 2018b) makes these sources even more interesting to study in further detail.

Previously, the photohadronic model was used to explain the multi-TeV flaring from many HBLs, including Mrk 501 (Sahu et al. 2019, 2020). This well studied Mrk 501 has shown EBL-like behavior, during VHE flaring in both 2005 and 2012 (Albert et al. 2007; Ahnen et al. 2018). So it is natural to extend the photohadronic scenario to explain the extraneous behavior of these flaring events. However, the photohadronic model in its standard form with EBL correction does not explain the VHE spectra, although most of the previous flarings were very well explained (Sahu et al. 2019). Here, for the first time, we demonstrate that the EBL-like behavior of Mrk 501 can be explained by the two-zone photohadronic model. The low-energy part of the spectrum is the standard HBL flaring event, and the high-energy part is due to the extreme nature of the event. We have also argued that these EBL-like events are transient in nature and may repeat in the future.

2. Photohadronic Model

The multi-TeV flaring from the HBLs is explained using the photohadronic model (Sahu 2019; Sahu et al. 2019). In this model, the Fermi-accelerated protons in the jet interact with the low-energy background seed photons through the $p^+ \rightarrow \Delta^+$ process, which subsequently decays into $\gamma$-rays through intermediate $p^0$ and to neutrinos via $\pi^+$. The neutrinos produced during the flaring period have energies of about half of the photon energy (Sahu 2019) and are not interesting from the IceCube point of view, as the energy is very low. The photohadronic scenario discussed here is based on the standard interpretation of the leptonic model, where the low- and high-energy peaks have a leptonic origin and the emitting region is a blob of comoving radius $R_0^+$ (where ‘+’ implies comoving frame), moving with a bulk Lorentz factor $\Gamma$ and Doppler factor $D$. The injected proton spectrum is a power law in its energy $E_p$ (Dermer & Schlickeiser 1993) as $dN/dE_p \propto E_p^{-\alpha}$, where the spectral index $\alpha \geq 2$. In order to produce the $\Delta^+$-resonance, the $E_p$ and the seed photon energy $\gamma$ must satisfy the kinematical condition (Sahu 2019),

$$E_p \gamma = \frac{0.32 \Gamma D}{(1+z)} \text{GeV}^2.$$

For HBLs, $\Gamma \approx D$ and $z$ is the redshift of the object. The observed VHE $\gamma$-ray has energy $E_\gamma = 0.1 E_p$.

In a canonical jet scenario the seed photon density is low, thus the efficiency for the $\Delta^+$-resonance process is low. So super-Eddington power in protons is required to account for the observed VHE flux (Cao & Wang 2014). To circumvent this problem, and based on evidence of a complex AGN jet structure during the multi-TeV flaring phase (Ghisellini et al. 2005), the photohadronic scenario assumes a double jet structure where an inner jet of size $R_0^+$ and photon density $n_{\gamma,0}$ is surrounded by an outer jet of size $R_0^+$ and photon density $n_{\gamma,0}^0$, with $R_0^+ < R_0^+$ and $n_{\gamma,0}^0 > n_{\gamma,0}$. The geometry of the double-jet scenario is shown in Figure 1 of Sahu (2019). Due to the adiabatic expansion of the jet, the photon density of inner jet decreases as it crosses into the outer jet. As the inner photon density is unknown, a scaling behavior is assumed (Sahu et al. 2019). This leads to the relation

$$n_{\gamma,0}^0(\gamma_{\gamma,1}) \approx n_{\gamma,0}^0(\gamma_{\gamma,2}),$$

$$n_{\gamma,0}(\gamma_{\gamma,1}) \approx n_{\gamma,0}(\gamma_{\gamma,2}).$$

This relation shows that during multi-TeV flaring, the ratios of the photon densities at energies $\gamma_{\gamma,1}$ and $\gamma_{\gamma,2}$ in the inner jet and the outer jet region are almost the same. The photon density in the outer region can be calculated from the observed flux and using Equation (2), we can express the inner photon density in terms of the observed flux. It is observed that, the range of $E_\gamma$ corresponds to the seed photon energy $\gamma$, in the low/energy tail region of the SSC spectrum and in this region the SSC flux is a perfect power law, given as $\Phi_{\gamma,SSC} \propto \gamma^{-\delta}$ (Sahu 2019). Moreover, the observed VHE $\gamma$-ray flux is proportional to the high-energy incident proton flux $F_p$ and the seed photon density in the jet background, $n_{\gamma,0}$. Using the relation in Equation (2) and taking into account the EBL correction (Franceschini et al. 2008), the observed multi-TeV spectrum is expressed in terms of the intrinsic flux $F_{\gamma,\text{in}}$ as

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

where $F_0$ is the normalization constant that can be fixed from the observed VHE spectrum and $\delta = \alpha + \beta$ is the only free parameter in this model. $F_{\gamma,\text{in}}$ is the intrinsic VHE gamma-ray flux. Previous studies have shown that $\delta$ lies in the range $2.5 \leq \delta \leq 3.0$. Moreover, flaring states can be roughly classified into three categories, depending on the value of $\delta$ as follows: (i) very high state with $2.5 \leq \delta \leq 2.6$, (ii) high state with $2.6 < \delta < 3.0$, and (iii) low state for $\delta = 3.0$ (Sahu et al. 2019).

As the proton spectral index is $\alpha \geq 2.0$, this automatically constrains the value of $\beta$ for a given $\delta$. But here we take $\alpha = 2$, which is the generally accepted value. The value of $\beta$ can be obtained independently by fitting the low-energy tail of the SSC SED from a simultaneous observation along with the VHE spectrum. However, simultaneous observations of the SSC SED in the tail region during the VHE flaring are rare and most of them are either nonsimultaneous or fitted using the leptonic models. The value of $\delta$ allows the flaring state for a given observation to be characterized without depending explicitly on the modeling of the SSC region.

3. Flaring History of Mrk 501

Mrk 501 ($z = 0.034$) is the second well known bright BL Lac object of HBL type and one of the brightest extragalactic sources in the X-ray/TeV sky. It was first detected in VHE by Whipple telescopes in 1996 (Abdo et al. 2009) and since then several major outbursts in multi-TeV have been observed and it has been the target of many multiwavelength campaigns mainly covering VHE flaring activities (Kataoka et al. 1999; Albert et al. 2008; Kranich 2009; Aleksić et al. 2015). The outburst of 1997 exhibited an unprecedented flare in VHE gamma-rays with an integral flux of up to 4 times the magnitude of the Crab.
As part of a multi-wavelength campaign from 2009 March 15 to August 1, it was observed by \( \sim 30 \) different instruments covering the entire electromagnetic spectrum (Aliu et al. 2016; Ahnen et al. 2017).

From 2005 May to June, Mrk 501 was observed for 30 nights with an overall observation time of 54.8 hr and flaring above 0.10 TeV was observed by the Major Atmospheric Gamma-ray Imaging Cherenkov Telescope (MAGIC) telescopes with an order of magnitude flux variation (Albert et al. 2007). On the nights of June 30 and July 9, flux doubling was observed within a time span of 2 minutes, which was the fastest flux variation ever observed from Mrk 501. During these two nights, the synchrotron peak as well as the high-energy peak were also shifted toward higher-energy limits, which is consistent with the EHBL interpretation of Mrk 501.

Similarly, during a multi-wavelength campaign between 2012 March and July, more than 25 instruments, including MAGIC, First G-APD Cherenkov Telescope (FACT), and Very Energetic Radiation Imaging Telescope Array System (VERITAS), were employed when flux above 0.2 TeV energy was observed (Ahnen et al. 2018). The highest activity occurred on June 9 with the peak flux of 0.3 CU around 0.2 TeV. It was observed that the spectral indices of both the X-ray and VHE gamma-ray were extremely hard, making it the hardest VHE spectra measured from Mrk 501 to date. Throughout this observation period, the synchrotron peak shifted above 5 keV and the SSC peak shifted above 0.5 TeV, which is EHBL behavior. Apart from the above active emission states, a few more VHE flaring events were observed (Chandra et al. 2017; Abdalla et al. 2019).

### 3.1. Multi-TeV EHBL-like Events

As discussed above, Mrk 501 was observed by MAGIC telescopes during 2005 May–July and an order of magnitude variation in VHE flux was observed (Albert et al. 2007). Marked enhancement in flux was observed on June 30 (3.48 ± 0.10 CU) and July 9 (3.12 ± 0.12 CU), when the source was in a very active state. During these two nights the synchrotron peaks were above \( 10^{17} \) Hz and the second peak position in both cases was also shifted toward higher energy.

As the photohadronic model is very successful in explaining the multi-TeV spectra of HBLs, by default, we use it first to fit these spectra before trying other options, and the best fits are shown in black curves in Figures 1 and 2. However, our fits are not good. Also, the observed spectra falls faster than the fitted curve and in the low-energy regime the behavior of the data and the curves is very different. We also fitted the VHE spectrum of 2012 June 9 (Ahnen et al. 2018), which is shown as the black curve in Figure 3. The fit is clearly poor. Also the observed spectrum falls faster than the fitted curve. It is clear that the standard photohadronic model does not adequately explain the observed spectra.

In the photohadronic scenario, the high-energy regime of the VHE spectrum is produced from the higher-energy part of the proton spectrum in the jet, and the low-energy regime of the VHE spectrum is from the lower part of the proton spectrum, both satisfying the kinematical condition in Equation (1). As \( E_{\gamma} \propto \varepsilon_{\gamma}^{-1} \), in EHBL flaring the SED is shifted toward higher energy compared to HBL flaring. As a result, the photohadronic...
model fails to explain the VHE spectrum simply because the seed photon flux is no longer a single power law.

Observationally, the transition from HBL to EHBL-like is the result of lateral displacement of both the peaks in the SED toward higher energies. As a result, jet parameters, such as bulk Lorentz factor, blob size, magnetic field, etc. may be different from HBL, but we assume that the mechanisms of particle acceleration and emission should remain the same. Therefore,

Figure 2. The VHE spectrum of Mrk 501 observed on the night of 2005 July 9. See Figure 1 for the definitions of the curves.

Figure 3. The VHE spectrum of Mrk 501 observed on the night of 2012 June 9. See Figure 1 for the definitions of the curves.
Figure 4. The VHE spectrum of Mrk 501 observed during 2012 May 22–27 is fitted with the photohadronic model (black curve) and the corresponding intrinsic spectrum is also shown (black dashed line). The spectral index $\delta = 2.9$ corresponds to a high emission state (Sahu et al. 2019).

Figure 5. The VHE spectrum of Mrk 501 observed in 2014 June 24 is fitted with photohadronic model (black curve) and the corresponding intrinsic spectrum is also shown (black dashed line). The spectral index $\delta = 2.93$ corresponds to a high emission state (Sahu et al. 2019).
the photohadronic process should still be dominant. We have already shown that a single power law does not adequately fit the observed spectrum, so we assume two power laws for the background seed photon flux in the SSC band, expressed as

\[ \Phi_{\text{SSC}} \propto \begin{cases} E_\gamma^{-\beta_1}, & 100 \text{ GeV} \lesssim E_\gamma \lesssim E_\gamma^{\text{ind}} \\ E_\gamma^{-\beta_2}, & E_\gamma \gtrsim E_\gamma^{\text{ind}} \end{cases} \] (4)

The spectral indices \( \beta_1 \) and \( \beta_2 \) are not equal (\( \beta_1 = \beta_2 \)), \( E_\gamma^{\text{ind}} \) is an energy scale around which the transition between zone-1 and zone-2 takes place and its value can be fixed from the individual flaring spectrum. Using this, the observed spectrum can be expressed as

\[ F_{\gamma, \text{obs}} = e^{-\gamma_{\text{cut}}} \times \begin{cases} F_1 \left( \frac{E_\gamma}{\text{TeV}} \right)^{-\delta_1 + 3}, & 100 \text{ GeV} \lesssim E_\gamma \lesssim E_\gamma^{\text{ind}} \quad \text{(zone-1)} \\ F_2 \left( \frac{E_\gamma}{\text{TeV}} \right)^{-\delta_2 + 3}, & E_\gamma \gtrsim E_\gamma^{\text{ind}} \quad \text{(zone-2)} \end{cases} \] (5)

where \( F_1 \) and \( F_2 \) are normalization constants and \( \delta_i = \alpha + \beta_i \) (\( i = 1, 2 \)) are the free parameters to be adjusted by fitting to the observed VHE spectrum. Using Equation (5), we can fit the observed VHE spectra of different EHBL flaring events of Mrk 501.

The VHE spectra of 2005 June 30 has 0.11 TeV \( \leq E_\gamma \leq 600 \) TeV and we can fit the low-energy part of the VHE spectrum (zone-1) with \( E_\gamma^{\text{ind}} \leq 1 \) TeV very well. The best fit is obtained for \( F_1 = 3.7 \times 10^{-10} \text{ erg cm}^{-2} \text{ s}^{-1} \) and \( \delta_1 = 2.77 \), with a statistical goodness of 99.9%. The best fit to the high-energy part (zone-2) is obtained for \( F_2 = 3.6 \times 10^{-10} \text{ erg cm}^{-2} \text{ s}^{-1} \) and \( \delta_2 = 3.26 \), with a statistical significance of 99.7%. These are shown in Figure 1 and compared with the standard photohadronic scenario. Both the zones are distinct and \( \delta_1 = \delta_2 \) and these give \( \beta_1 = 0.77 \) and \( \beta_2 = 1.26 \). Thus, we conclude that the background seed photon fluxes in zone-1 and zone-2 have different behavior.

The second VHE flaring was observed on 2005 July 9 in the energy range 0.11 TeV \( \leq E_\gamma \leq 4.35 \) TeV. In zone-1 (\( E_\gamma^{\text{ind}} \leq 600 \) GeV) the best fit to the spectrum is obtained for \( F_1 = 2.9 \times 10^{-10} \text{ erg cm}^{-2} \text{ s}^{-1} \) and \( \delta_1 = 2.84 \), with a statistical goodness of 99.3%. Similarly, in zone-2 the best fit is achieved with \( F_2 = 2.2 \times 10^{-10} \text{ erg cm}^{-2} \text{ s}^{-1} \) and \( \delta_2 = 3.2 \), with a statistical goodness of 99.9%. Here the two zones are distinct, but can be joined smoothly.

Taking two different values of bulk Lorentz factor (\( \Gamma = 25 \), 50), the multwavelength SEDs were constructed to explain the flaring events of June 30 and July 9 (Albert et al. 2007). Although these fit the observed spectra well, the minimum values of the SSC energy for both \( \Gamma \)’s are very high (\( \epsilon_\gamma \approx 94.6 \text{ MeV} \) and 31.7 MeV respectively). Assuming these values of \( \epsilon_\gamma \) correspond to the maximum observed \( E_\gamma \), we obtain unrealistically very high values of \( \Gamma \) for both the flares (for June 30, \( \Gamma \approx 138 \), 80 and for July 9, \( \Gamma \approx 117 \), 68). For a reasonable estimate of \( \Gamma \), the minimum \( \epsilon_\gamma \) must be small (\( \epsilon_\gamma < 10 \text{ MeV} \)).

During the multwavelength campaign between 2012 March and July, the highest activity in VHE was observed on June 9 in the energy range 0.25 TeV \( \leq E_\gamma \leq 6.72 \) TeV (Ahnen et al. 2018). Zone-1 of its VHE spectrum (\( E_\gamma^{\text{cut}} \leq 600 \) GeV) is fitted very well with \( F_1 = 2.9 \times 10^{-10} \text{ erg cm}^{-2} \text{ s}^{-1} \) and \( \delta_1 = 2.84 \), with a statistical goodness of 99.9%. Similarly, the best fit to zone-2 is achieved with \( F_2 = 3.7 \times 10^{-10} \text{ erg cm}^{-2} \text{ s}^{-1} \) and \( \delta_2 = 3.5 \), with a statistical goodness of 93.8%. We have also estimated the \( \Gamma \) for this flaring event using the multiwavelength SED of one-zone and two-zone leptonic models (Ahnen et al. 2018). In both cases, the minimum SSC energy is \( \epsilon_\gamma \approx 3.36 \times 10^{20} \text{ Hz} \) (\( \approx 1.39 \text{ MeV} \)), which gives \( \Gamma \approx 18 \), a more reasonable value than previous estimates. By taking the central black hole mass as \( M_{\text{BH}} \approx 2 \times 10^{8} \text{ M}_\odot \), the Eddington luminosity of Mrk 501 is \( L_{\text{Edd}} \approx 2.5 \times 10^{47} \text{ erg s}^{-1} \), which has to be equally shared by the jet and the counter jet. The highest integrated \( \gamma \)-ray luminosity above 100 GeV is obtained for the June 30 flaring event, which is \( L_\gamma \approx 2.4 \times 10^{46} \text{ erg s}^{-1} \). The proton luminosity should satisfy \( L_p = 7.5 L_{\gamma,\text{max}} < L_{\text{Edd}}/2 \), which corresponds to \( \Gamma \approx 0.15 \), and by taking \( \Gamma \approx 0.2 \), we get \( L_p \approx 8.9 \times 10^{46} \text{ erg s}^{-1} \) which is less than the Eddington luminosity.

In the photohadronic model, the maximum proton energy is \( E_p^{\text{max}} \approx 10 L_{\gamma,\text{max}} \). In the above flaring periods we observed that, \( E_p^{\text{max}} \approx 7 \text{ TeV} \), which corresponds to \( E_p^{\text{max}} \approx 70 \text{ TeV} \). Thus, the protons accelerated in the blazar jet are not energetic enough to be observed by cosmic-ray detectors on Earth. Additionally, these protons can be deflected by the galactic magnetic field and will be difficult to correlate with the source. Since the EBL energy is very low, in the present context the pion production through photopion process and the subsequent secondary photon production from neutral pions are also negligible.

From the above analysis we observe that the VHE spectrum in zone-1 is a standard HBL flaring event and all the flaring spectra correspond to high states (2.6 < \( \delta_i < 3.0 \)). This implies that the seed photon spectral indices for these emission states should have 0.4 < \( \beta_i < 1.0 \). On the contrary, the spectra in zone-2 have different behaviors, with \( \delta_2 \geq 3.1 \). So far we have not come across any HBL flaring event that has a spectral index \( \delta > 3.0 \). Thus, \( \delta_2 \geq 3.1 \) does not correspond to any of the HBL emission states. This is a new contribution from the EBL-like behavior of the flaring event. The above value of \( \delta_2 \) implies \( \beta_2 \geq 1.1 \). As the proton spectral index is the same for both the zones, it is the distribution of the background seed photons in the SSC region that decides the nature of the emission state of a VHE flaring event. Thus, the EBLH nature of the spectrum must be attributed to the SSC band where \( \beta_2 \geq 1.1 \). But what could be the origin of this higher value of \( \beta_2 \)? The leptonic models of many HBL SEDs have deep valleys at the junction of the synchrotron spectrum and the SSC spectrum with \( \beta \approx 1.1 \) (Sahu et al. 2017, 2018), and Fermi-accelerated protons colliding in this region of the seed photon background will produce zone-2 of the spectrum. Perhaps the inverse Compton scattering of high-energy electrons with the self-produced synchrotron photons during extreme events produces the SSC SED with \( \beta \geq 1.1 \).

Are these transitions temporary? To address this question, we first must analyze some of the flaring events from Mrk 501 before and after these extreme emission states.

1. Observation of Mrk 501 during a multwavelength campaign covering a period of 4.5 months from 2009 March 15 to August 1 (Ahnen et al. 2017) by Whipple, VERITAS, and MAGIC telescopes observed three different VHE emission states, and all of them are consistent with the standard flaring of an HBL. Also these
flarings are best explained using a photohadronic model (Sahu et al. 2020).

2. The TACTIC telescope performed observation in TeV energy to Mrk 501 between 2012 April 15 to May 30, for about 70.6 hr and during May 22–27, the source was in a high emission state (Chandra et al. 2017). The observed VHE spectrum was consistent with the HBL emission and can also be explained very well using the photohadronic scenario. We have shown the best fit of our model to the VHE spectrum in Figure 4. However, after a few days, i.e., on June 9, the observed VHE emission was EHBL-like.

3. On 2014 June 24, the HESS telescopes observed Mrk 501 for a total of 1.8 hr in four consecutive runs when rapid flux variability in multi-TeV energy was observed (Abdalla et al. 2019). Once again, this VHE spectrum was perfectly consistent with the HBL flaring and undoubtedly it was in a high emission state, as explained by the photohadronic model (Sahu et al. 2019), which is shown in Figure 5.

The above three episodes of standard HBL flaring of Mrk 501 before and after the extreme flaring events of 2005 and 2012 suggest that the EHBL-like events are transient and may repeat in the future.

4. Discussion

The well known and extensively observed nearby HBL, Mrk 501 has undergone several episodes of multi-TeV flaring since its discovery in 1996. Two flaring events, one in 2005 and another in 2012, are of special significance, since these events were EHBL-like. Usually, the flaring events of HBLs can be explained using the photohadronic model, in which the VHE gamma-rays are produced as secondaries from the $p\gamma \rightarrow \Delta^+$ process. However, we found it inadequate for explaining the extraneous nature of these EHBL-like events, as the VHE flux does not follow a single power law. In our work, we assume that even after the transition from HBL to EHBL, the mechanisms of particle acceleration and emission are still the same and the photohadronic scenario is the dominant process producing VHE gamma-rays. We also invoke the two-zones scenario for the SSC seed photons, which naturally divides the observed VHE spectrum into two separate zones. Using the two-zones photohadronic model we can explain the VHE spectrum very well.

We find that the low-energy regime of the spectrum (zone-1) is the standard HBL flaring in VHE with $2.5 < \delta_1 < 3.0$. However, zone-2 has $\delta_2 \geq 3.1$, which is a new contribution due to the EHBL-like nature of the flaring event. We also estimated the bulk Lorentz factor $\Gamma$ of the jet during the extreme flaring epochs, which gave very high values for the 2005 flaring events and $\Gamma \sim 18$ for the 2012 event.

Many more episodes of multi-TeV flaring from Mrk 501 were observed before and after the EHBL-like events. Undoubtedly, all these events can be explained by photohadronic process. From the above observations we argued that EHBL-like events in Mrk 501 are transient and may repeat in the future. However, we need to observe this extreme behavior from other well studied HBLs to further corroborate our claim.

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