Extreme HBL-like Behavior of Markarian 421 and Its Two-zone Photohadronic Interpretation

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Abstract

Markarian 421 is the nearest high-energy peaked blazar and is also the first extragalactic source to be detected in multi-TeV γ-rays. It has been observed in multiwavelength for an exceptionally long period of time with dense monitoring and several major outbursts have been detected from this source. In 2010 March, the source was in a high state of activity and was observed in multiwavelength by various telescopes for 13 consecutive days. During this period the position of the synchrotron peak was found to be above 10^{17} Hz and also the position of the second peak was shifted toward higher energy, a signature of extreme HBL-like behavior. We observed that the standard photohadronic model is inadequate to explain the observed spectra. However, a recently proposed two-zone photohadronic model explains very well the GeV–TeV flaring events observed by both MAGIC and VERITAS telescopes. From the observation of the highest energy γ-ray event on MJD 55266 we also estimated the minimum bulk Lorentz factor.

Unified Astronomy Thesaurus concepts: High energy astrophysics (739); Blazars (164); Relativistic jets (1390); BL Lacertae objects (158); Gamma-rays (637)

1. Introduction

The spectral energy distributions (SEDs) of blazars are characterized by two non-thermal peaks (Dermer & Schlickeiser 1993). The first peak, in the infrared to X-ray energy range, is produced by the synchrotron emission from relativistic electrons in the jet. The second peak, in between X-ray and γ-ray energy, 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 (EC) scattering with external sources such as photons from the accretion disk or broad-line regions (Sikora et al. 1994; Blazejowski et al. 2000). The model that explains these two peaks is in general referred to as the leptonic model. Depending on the position of the synchrotron peak, the blazars are classified into four categories: low-energy peaked blazars (LBLs, \( \nu_{\text{syn}} < 10^{14} \) Hz), intermediate-energy peaked blazars (IBLs, \( \nu_{\text{peak}} \) between \( 10^{14} \) Hz and \( 10^{15} \) Hz), high-energy peaked blazars (HBLs, \( \nu_{\text{peak}} \) between \( 10^{15} \) Hz and \( 10^{17} \) Hz; Abdo et al. 2010), and extreme energy peaked blazar (EHBL, \( > 10^{17} \) Hz; Costamante et al. 2001). In particular, the EHBLs are characterized by low luminosity and have limited variabilities, which make these objects difficult to detect (Costamante et al. 2018; Acciari et al. 2020b).

So far, only a few EHBLs have been detected in the very high-energy (VHE, \( > 100 \) GeV) regime and among them some well-known objects are 1ES 0229+200, 1ES 0347-232, RGB J0710+591, and 1ES 1101-232 (Costamante et al. 2018). Among all the EHBLs observed so far, the highest energy peak frequencies correspond to 1ES 0229+200 with the synchrotron peak at \( \nu_{\text{syn}} \approx 3.5 \times 10^{19} \) Hz and the SSC peak at \( \nu_{\text{SSC}} \approx 1.5 \times 10^{27} \) Hz (Kaufmann et al. 2011), respectively. The nearest and the extensively studied HBLs Markarian 421 (Mrk 421), Markarian 501 (Mrk 501), and 1ES 1959+650 have also shown EHBL-like behavior with harder TeV spectra, in which the synchrotron and SSC peaks are shifted toward higher energy during some flaring episodes (Aleksić et al. 2015a; Ahnen et al. 2018; Acciari et al. 2020a). The EHBL-like behavior of Mrk 501 was observed during two episodes of very high-energy flaring events of May to July 2005 and 2012 June. Also, during a multiwavelength (MW) campaign of 1ES 1959+650 between 2016 April 29th and November 21st, the MAGIC telescopes observed multi-TeV flaring events during the nights of 2016 June 13th, 14th, and July 1st when the position of the synchrotron peak was in EHBL range and exhibiting extreme HBL-like behavior.

It is very difficult to explain the shift of the second peak in the one-zone leptonic model. However, it has been shown that by using unrealistic model parameters, such as the large values of minimum electron Lorentz factor and the bulk Lorentz factor (Ahnen et al. 2018; Acciari et al. 2020a) as well as a low magnetic field, the shift can be explained. Alternative solutions have also 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 hadrionic model (Böttcher et al. 2008; Ahnen et al. 2018; Acciari et al. 2019).

In previous studies, Sahu et al. (2019, 2020b) have used the photohadronic model to explain the multi-TeV flaring from many HBLs very well. In all these studies it is shown that the Fermi-accelerated high-energy protons interacting with the seed SSC photons in the jet can explain the VHE spectrum very well. The SSC photon flux \( \Phi_{\text{SSC}} \) in this region is a perfect power law given as \( \Phi_{\text{SSC}} \propto \epsilon^{-\gamma} \propto E_{\gamma}^{-\beta} \) (in units of erg cm\(^{-2}\) s\(^{-1}\)), where \( \epsilon_{\gamma} \) is the seed photon energy, \( E_{\gamma} \) is the energy of the observed VHE gamma-ray, and \( \beta \) is the seed photon spectral index. The value of \( \beta \) lies in the range \( 0 < \beta < 1 \). However, recently, Sahu et al. (2020a, 2021) have
shown that this standard photohadronic scenario is inadequate to explain the EHBL-like behavior of the flaring events of Mrk 501 and 1ES 1959+650. It was also shown that the seed SSC photon flux in the kinematically allowed region for the $\Delta$-resonance production from $p\gamma$ interaction is no longer a single power law due to the EHBL-like behavior of the flaring events. So, the standard photohadronic model was extended to include two different zones for the SSC flux. The zone-1 (low energy) region has the conventional behavior $0 < \beta \leq 1$. In the zone-2 (high energy) region the value of $\beta$ is different and in the range $1 < \beta \leq 1.5$. However, the spectral index $\alpha$ of Fermi-accelerated high-energy protons in both the zones remain the same.

During the EHBL-like flaring events of Mrk 501 and 1ES 1959+650, the positions of the synchrotron peak and the SSC peak were shifted toward the higher energies. So, Sahu et al. (2019a) assumed that the transition from HBL to EHBL-like behavior is due to the shift of the synchrotron peak and the SSC peak in the SED toward higher energies. As a result of this shift, jet parameters such as bulk Lorentz factor, blob size, and magnetic field may be different from HBL, but the particle acceleration and emission mechanisms remain the same. Therefore, the photohadronic process should still be the dominant process in this changed environment. It is also argued that these EHBL-like events are transient in nature and may repeat in the future.

During a MW campaign in 2010, flaring in GeV–TeV energy was observed in Mrk 421. The VHE activity started decreasing from a high flux to a normal flux during the period from March 10–22, i.e., for 13 consecutive days (Aleksić et al. 2015a). It was observed that the positions of both the synchrotron peak and the SSC peak of Mrk 421 were shifted toward higher energy values consistent with the EHBL synchrotron peak and the SSC peak of Mrk 421 were shifted decreasing from a high energy was observed in Mrk 421. The VHE activity started almost the same bulk Lorentz factor, blob size, and magnetic field may be different from HBL, but the particle acceleration and emission mechanisms remain the same. Therefore, the photohadronic process should still be the dominant process in this changed environment. It is also argued that these EHBL-like events are transient in nature and may repeat in the future.

2. Flaring of Mrk 421

Mrk 421 is the nearest ($z = 0.031$) well-known HBL with a central black hole mass $M_B \approx (2–9) \times 10^8 M_\odot$ and is the first extragalactic source to be detected in multi-TeV $\gamma$-rays (Punch et al. 1992). It is also one of the fastest varying $\gamma$-ray sources. Since its discovery, the object has been studied intensively through dedicated MW observations and several major flares have been observed (Amenomori et al. 2003; Cui et al. 2005; Fossati et al. 2008; Mastichiadis et al. 2013; Abeysekara et al. 2017; Beck et al. 2020). Its average MW SED has been modeled with both leptonic (Abdo et al. 2011; Banerjee et al. 2019) and hadronic (Cerruti et al. 2015; Zech et al. 2017) models. During 1994 April–May, a TeV/X-ray flare was reported and on May 14/15 a correlation between the TeV emission and X-ray flare was observed. Also, during a multiwavelength campaign in 2004, large flares in X-ray by the Rossi X-ray Timing Explorer and TeV flare by the Whipple 10 m telescope were observed (Błażejowski et al. 2005). It is important to note that during this period, the TeV flare had no coincident low-energy counterparts, and most significantly, the X-ray flux reached its peak 1.5 days before the TeV flux during this outburst. A remarkable similarity between this VHE flare and the orphan TeV flare in 1ES 1959+650 of 2002 (Krawczynski et al. 2004) and a similar variation pattern in their X-ray emission was established. Exceptionally long and dense monitoring in MW of Mrk 421 has been undertaken since 2009 to understand the temporal evolution of the SED. Mrk 421 was in active state during a MW campaign in 2010 and an extraordinary flare $\sim$27 Crab Unit (c.u.) above 1 TeV was first detected by VERITAS telescopes on February 16 and a follow-up observation was undertaken by the HESS telescopes (Tluczykont 2010) for four subsequent nights. So far, this is the highest flare ever observed from Mrk 421. Also, flaring in VHE gamma-ray was observed for 13 consecutive days from March 10 (MJD 55265) to March 22 (MJD55277). Again, during a 6-month long multi-instrument campaign (Banerjee et al. 2019), a large VHE flare about 16 times larger than the usual one was observed by MAGIC telescopes on 2014 April 25th and soon it was followed-up by XMM-Newton and VERITAS. Several of the above multi-TeV flaring events from Mrk 421 have been explained extremely well by the standard photohadronic scenario (Sahu et al. 2016, 2018, 2019).

3. Two-zone Photohadronic Model

The photohadronic model is very successful in explaining the multi-TeV flaring events from many HBLs (Sahu et al. 2019; Sahu 2019). The epoch of VHE flaring is explained by assuming the formation of a double jet structure along the same axis: an inner jet of size $R_i$ and photon density $n_{i,\gamma}$ buried under an outer jet of size $R_o$ and photon density $n_{o,\gamma}$ where $R_i \leq R_o$ and $n_{i,\gamma} > n_{o,\gamma}$. Here the notation $\cdot$ implies a comoving frame. The internal and the external jets are moving with almost the same bulk Lorentz factor $\Gamma_{in} \simeq \Gamma_{ext} \simeq \Gamma$. Also, their common Doppler factor is $\mathcal{D}$ (for blazars $\Gamma \simeq \mathcal{D}$). The geometrical structure of the jet and the detailed description of the photohadronic model is given in Figure 1 of Sahu (2019).

In the inner jet region the Fermi-accelerated protons with a resonance and its subsequent decay gives $\gamma$-rays and neutrinos via the decay of neutral pions and charged pions, respectively. As the inner region is hidden, there is no way to directly estimate the photon density there. Thus we assume a simple scaling behavior of the photon densities in the inner and the outer jet regions satisfying the criteria

$$\frac{n_{i,\gamma}(\epsilon_{\gamma,1})}{n_{o,\gamma}(\epsilon_{\gamma,2})} \approx \frac{n_{i,\gamma}'(\epsilon_{\gamma,1})}{n_{o,\gamma}'(\epsilon_{\gamma,2})}. \quad (1)$$

The above equation implies that the ratio of photon densities at two different background energies $\epsilon_{\gamma,1}$ and $\epsilon_{\gamma,2}$ in the inner and the outer jet regions are almost the same. By using the relation in Equation (1), we can express the inner photon density in terms of the observed flux. The kinematical condition
(Sahu 2019) to produce the $\Delta$-resonance is

$$E_p \epsilon_\gamma = \frac{0.32 \Gamma D}{(1 + z)^3} \text{GeV}^2,$$

where $z$ is the redshift of the object. The observed VHE $\gamma$-ray energy $E_\gamma$ and the proton energy $E_p$ are related through $E_\gamma \simeq 0.1 E_p$. In previous works by Sahu (2019) it is explicitly shown that for the production of $\Delta$-resonance, the value of $\epsilon_\gamma$ always lies in the lower tail region of the SSC band and for HBLs the flux in this region is a perfect power law.

The VHE $\gamma$-rays en route to Earth undergo energy dependent attenuation by the extragalactic background light (EBL) through electron–positron pair production and this pair-production process not only attenuates the absolute flux but also significantly changes the shape of the VHE spectra. The measurement of the EBL is very difficult due to the uncertainties in the contribution of zodiacal light (Häuser & Dwek 2001; Chary & Pope 2010) and consequently galaxy counts result in a lower limit since the number of unresolved sources are unknown (Pozzetti & Madau 2001). Several approaches with different degrees of complexity have been developed to calculate the EBL density as a function of energy for different redshifts (Stecker et al. 2006, 2016; Franceschini et al. 2008; Domínguez et al. 2011; Inoue et al. 2013). For the present analysis we use the EBL model of Franceschini et al. (2008), which is consistent with a EBL peak of $\sim 15$ nW m$^{-2}$ sr$^{-1}$ at 1.4 $\mu$m and is also widely used in other leptonic and hybrid models (Aleksić et al. 2015b; Ahnen et al. 2017). Taking into account the EBL contribution the observed VHE flux from the sources can be given as (Sahu 2019)

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

where $A_\gamma$ is a dimensionless constant and $\tau_{\gamma\gamma}$ is the optical depth for the $\gamma\gamma \rightarrow e^+ e^-$ process, which depends on $E_\gamma$ and the redshift. In the standard photohadronic model, $\Phi_{\text{SSC}} \propto E_\gamma^{-\beta_1}$ and by putting this in Equation (3) the flux can be written as

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

The normalization constant $F_0$ is deduced from the observed VHE spectrum. Thus the spectral index $\delta = \alpha + \beta_1$ is the only free parameter in this model and $F_{\gamma, \text{in}}$ is the intrinsic VHE $\gamma$-ray flux. In previous studies (Sahu et al. 2020a, 2021) it was shown that the EHBL-like behavior of the flaring epoch cannot be explained by the canonical photohadronic model. In order to remedy this defect the tail region of the SSC band, which is responsible for the production of the $\Delta$-resonance, is assumed to have two different power-laws with spectral indices $\beta_1$ (lower part of the tail region) and $\beta_2$ (upper part of the tail region). Thus the photon flux is expressed as

$$\Phi_{\text{SSC}} \propto \begin{cases} E_\gamma^{-\beta_1}, & 100 \text{ GeV} \lesssim E_\gamma \lesssim E_\gamma^{\text{ind}} \\ E_\gamma^{-\beta_2}, & E_\gamma \gtrsim E_\gamma^{\text{ind}} \end{cases}.$$  

Here $\beta_1 \neq \beta_2$ and $E_\gamma^{\text{ind}}$ is an energy scale around which the transition takes place and its value can be fixed from the individual flaring spectrum. We suppose that the change in the value of the spectral index from $\beta_1$ to $\beta_2$ around $E_\gamma^{\text{ind}}$ could be due to the effect of the magnetic field on the energy loss process of the high-energy electrons to the SSC photons or it could be some new physics. However, we do not dwell on the transition between these two zones as the exact physical mechanism behind it is unclear at this stage. The value of $E_\gamma^{\text{ind}}$ corresponds to a value of $\epsilon_\gamma$ in the SSC band. This separates $\Phi_{\text{SSC}}$ into two distinct regions. By inserting Equation (5) into Equation (3), the observed VHE spectrum can be expressed as

$$F_{\gamma, \text{obs}} = e^{-\tau_{\gamma\gamma}} \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}} \text{ (zone - 1)} \\ F_2 \left(\frac{E_\gamma}{\text{TeV}}\right)^{-\delta_2 + 3}, & E_\gamma \gtrsim E_\gamma^{\text{ind}} \text{ (zone - 2)}. \end{cases}\)
The VERITAS telescopes observed the flaring of Mrk 421 on MJD 55260, 55265, 55267-55274 with a 10 min run time each day. The observations were performed at zenith angles 18°–23° to benefit from the lowest possible energy threshold of the events. Also, the Whipple 10 m telescope performed ten observations in ON/OFF and TRK (tracking) modes (Pichel 2009), lasting from one to six hours each on MJD 55267-55271 and MJD 55273-55277.

The most important aspect of these 13 days of observation is that the synchrotron peak and the SSC peaks were displaced toward higher energies. Particularly, the synchrotron peak frequency was above 10^{14} Hz and according to the classification scheme of the BL Lac objects, it belongs to the EHBL category even though Mrk 421 is well known as an HBL. As discussed in the introduction, similar behavior has also been observed from Mrk 501 and 1ES 1959+650, which are well-known HBLs, and their spectra are explained very well with the two-zone photodahronic scenario (Sahu et al. 2020a, 2021). Thus, using the two-zone photodahronic model, the 13 days of VHE flaring events observed by MAGIC and VERITAS are analyzed here. For comparison, the one-zone SSC fits are also shown along with our results (Aleksić et al. 2015a). In this analysis, we ignore the statistical significance of a fit when only three or less observed data points are available.

The VHE spectrum of MJD 55265 (2010 March 10) observed by both MAGIC and VERITAS is in the energy range 0.1 TeV \lesssim E_\gamma \lesssim 4.3 TeV and the synchrotron peak is at \epsilon_0 \sim 4.6 \times 10^{17} Hz, which clearly shows its EHBL behavior.

Using the two-zone photodahronic model, we fit the low-energy part of the spectrum (zone-1; for \mathrm{E}_{\text{phot}} \lesssim 1 \text{ TeV}) very well with \delta_1 = 2.7 and its corresponding flux normalization is \mathrm{F}_1 = 2.1 \times 10^{-10} \text{ erg cm}^{-2} \text{ s}^{-1}, with a statistical significance of 98% (\chi^2 = 0.0008). Also, the best fit to the high-energy part of the VHE spectrum (zone-2) is obtained for \mathrm{F}_2 = 2.0 \times 10^{-10} \text{ erg cm}^{-2} \text{ s}^{-1} and \delta_2 = 3.2, with a statistical significance of 96% (\chi^2 = 0.0366). These are shown in Figure 1(a) along with the one-zone SSC model of Aleksić et al. (2015a) for comparison. It can be seen that our model fits the data better than the one-zone SSC model. The zone-1 and zone-2 regions have their respective seed SSC flux spectral indices \beta_1 = 0.7 and \beta_2 = 1.2. The VERITAS data behave differently in its highest energy when the flux has suddenly gone up and is incompatible with the two-zone model. However, previously it was shown that this can be fitted well with the conventional photodahronic model with \mathrm{F}_0 = 2.1 \times 10^{-10} \text{ erg cm}^{-2} \text{ s}^{-1} and \delta = 2.6, corresponding to a very high-emission state (Sahu et al. 2019). As the MAGIC and VERITAS observation windows are seven hours apart, it is possible that intra-night variability might be responsible for this difference.

On MJD 55266 the flaring event was observed by MAGIC telescopes only and the spectrum is in the energy range 0.1 \text{ TeV} \lesssim E_\gamma \lesssim 4.4 \text{ TeV}. The bow shape spectrum on this day (MJD 55266) cannot be fitted by a single power law. The zone-1 (\mathrm{E}_{\text{phot}} \lesssim 1 \text{ TeV}) is fitted with \delta_1 = 2.7 and \mathrm{F}_1 = 2.5 \times 10^{-10} \text{ erg cm}^{-2} \text{ s}^{-1} with a statistical significance of 99% (\chi^2 = 0.0189). Similarly, the best fit to zone-2 is obtained for \mathrm{F}_2 = 2.45 \times 10^{-10} \text{ erg cm}^{-2} \text{ s}^{-1} and \delta_2 = 3.5, with a statistical significance of 82% (\chi^2 = 0.0008) and on this day the synchrotron peak is at \epsilon_0 \sim 5.0 \times 10^{17} Hz. Our fit and the one-zone SSC results are compared in Figure 1(b). It can be seen that the leptonic model is unable to fit the data in the low-energy regime.

The only data available on MJD 55267 are from VERITAS and the spectrum is very well fitted with the two-zone photodahronic scenario with the transition energy \mathrm{E}_{\text{phot}} \approx 1 \text{ TeV}, which is shown in Figure 2(a). The best fitted values for zone-1 are \mathrm{F}_1 = 2.5 \times 10^{-10} \text{ erg cm}^{-2} \text{ s}^{-1} and \delta_1 = 2.7 (statistical significance of 83%, \chi^2 = 0.0538) while for zone-2 we have \mathrm{F}_2 = 2.5 \times 10^{-10} \text{ erg cm}^{-2} \text{ s}^{-1} and \delta_2 = 3.3. The SSC model of Aleksić et al. (2015a) predicts a VHE spectrum that falls significantly faster than the observed spectrum.

Both MAGIC and VERITAS observed the flaring event of MJD 55268 and the observed spectra are in the energy range 0.18 \text{ TeV} \lesssim E_\gamma \lesssim 2.1 \text{ TeV}. The MAGIC spectrum is well fitted in zone-1 with the spectral index \delta_1 = 2.7 and the normalization factor \mathrm{F}_1 = 1.3 \times 10^{-10} \text{ erg cm}^{-2} \text{ s}^{-1} and here \mathrm{E}_{\text{phot}} \lesssim 0.8 \text{ TeV}. There are not many data points in zone-2, so we fitted this region with \delta_2 = 3.4, 3.5 and both values fit very well to the observed data. However, above 2 TeV there is a minor difference between these fits. Also our fit to the spectrum differs substantially from the one-zone SSC fit as shown in Figure 2(b).

The flaring event of MJD 55269 is very similar to the one observed on MJD 55268 and a good fit to the spectrum is achieved with \mathrm{F}_1 = 2.0 \times 10^{-10} \text{ erg cm}^{-2} \text{ s}^{-1} and \delta_1 = 2.7 for zone-1 (statistical significance of 96%, \chi^2 = 0.0790), while
\( F_2 = 1.8 \times 10^{-10} \text{ erg cm}^{-2} \text{s}^{-1}, \) \( \delta_2 = 3.2 \) are for zone-2 as shown in Figure 3(a).

On MJD 55270 the spectrum in the low-energy regime, i.e., zone-1, is flatter than previous days, which implies that the flaring event is moving toward a low-emission state. However, because of a smaller number of data points we fitted this region with \( \delta_1 = 2.7, 2.8 \) and both fit very well with very similar normalization constants \( (F_1 = 1.32 \times 10^{-10} \text{ erg cm}^{-2} \text{s}^{-1} \) and \( 1.16 \times 10^{-10} \text{ erg cm}^{-2} \text{s}^{-1})). \) On the other hand, zone-2 is fitted well by \( F_2 = 8.7 \times 10^{-11} \text{ erg cm}^{-2} \text{s}^{-1}, \) \( \delta_2 = 3.3 \) (statistical significance of 87%, \( \chi^2 = 0.0339 \)) as shown in Figure 3(b).

The one-zone SSC model also fits well to the spectrum. In the high-energy regime, however, it falls faster than our fit.

The flaring event of MJD 55271 was only observed by VERITAS in the energy range \( 0.25 \text{ TeV} \lesssim E_\gamma \lesssim 2.6 \text{ TeV}. \) Below the transition energy \( E_\gamma \lesssim 0.9 \text{ TeV}, \) the zone-1, we can fit well the spectrum with \( F_1 = (1.7 - 1.62) \times 10^{-10} \text{ erg cm}^{-2} \text{s}^{-1} \) and \( \delta_1 = (2.8 - 2.9). \) The zone-2 region is fitted with \( F_2 \simeq 1.55 \times 10^{-10} \text{ erg cm}^{-2} \text{s}^{-1} \) and \( \delta_2 = 3.3. \) The one-zone SSC model fit is also shown in Figure 4(a) to compare with our two-zone photohadronic model fit.
For the observations from MJD 55272 to MJD 55277, with the exception of MJD 55275 when there was no observation, the value of $E_{\text{min}}$ is very low and in a narrow range of 0.25 TeV $\lesssim E_{\gamma}^{\text{min}} \lesssim 0.4$ TeV. Also, the spectrum for each individual day is flat, which is best fitted with either $\delta_1 = 2.9$ or 3.0, and the statistical significance for these fits ranges from 85% to 95%. This value of $\delta_1$ signifies that the flaring of Mrk 421 has reached the low-emission state and at the same time the seed photon flux in the SSC band has reached the maximum value of $\beta_1 \approx 1.0$. Also the maximum photon flux in zone-1 has substantially decreased compared to the first day of the observation. The zone-2 region for these five days is also fitted very well with $3.2 \lesssim \beta_2 \lesssim 3.5$, which corresponds to the seed photons in the low-energy tail region of the SSC band and their fluxes having spectral indices in the range $1.2 \lesssim \beta_2 \lesssim 1.5$. The flaring events of all these days along with the one-zone SSC fits are shown in Figure 4(b) and Figures 5(a), (b), (c) and (d), respectively.

Initially the VHE flaring was in the high-emission state and slowly it went down to the low-emission state by the end of the flaring period. This transition was accompanied by a gradual decrease in the transition energy $E_{\gamma}^{\text{min}}$ from $\sim 1$ TeV to $\sim 0.25$ TeV and consequently zone-2 became wider and spread into zone-1 making the latter region narrower. We recall that the transition in the VHE spectrum took place due to the change in the seed SSC photon flux. So, physically this means that initially the photon flux in the tail region of the SSC band, which is responsible for the $\Delta$-resonance production, had two distinct energy dependencies as shown in Equation (5) (lower part with $\epsilon^{\beta_1}$ and upper part with $\epsilon^{\beta_2}$). Slowly the lower part drifted into the upper part by squeezing the former region into a narrow strip.

On MJD 55266, the maximum observed $\gamma$-ray energy was $E_{\gamma} \approx 4.4$ TeV, which is produced from the interaction of Fermi-accelerated protons of energy $E_p \approx 44$ TeV in the jet with the photons in the lower part of the SSC spectrum. In the two-zone SSC model of Aleksic et al. (2015a) for this day the SSC spectrum starts around $\epsilon_{\gamma} \approx 7 \times 10^{21}$ Hz (Figure 8(b) of Aleksic et al. 2015a). For this value of $\epsilon_{\gamma}$, the minimum value of the bulk Lorentz factor estimated in our model is $\Gamma \approx 21$. Similar or smaller values for the bulk Lorentz factor are obtained for other days. On the other hand, in the one-zone SSC model (Figure 8(a) of Aleksic et al. 2015a), the SSC spectrum starts above $2 \times 10^{21}$ Hz and for this value of $\epsilon_{\gamma}$ we get minimum $\Gamma \approx 35$, which is too high.

5. Discussion

Mrk 421 is the nearest HBL and is the first extragalactic source to be observed in VHE. Since then it has undergone several episodes of multi-TeV flaring. Mrk 421 is also the first source observed in multiwavelengths for an exceptionally long period of time with dense monitoring. The VHE flaring epochs of this source during all its previous observations were consistently found to be in the HBL category, which corresponds to the synchrotron peak in the frequency range $10^{15}$–$10^{16}$ Hz. However, during the 13 consecutive days of observations undertaken during 2010 March the source was in a state of high activity with a changed spectral behavior and the synchrotron as well as the second peak shifted toward higher energies. The synchrotron peak shifted above $10^{17}$ Hz, implying that the blazar has undergone a shift from HBL to EBL. Similar situations are observed in HBLs Mrk 501 and 1ES 1959+650, which were explained very well by the two-zone photohadronic scenario. For Mrk 421, we have used the
same two-zone photohadronic model to interpret the 13 consecutive days of flaring in VHE and we find that the individual flaring events are explained very well by our model. This shows once more the success of the two-zone photohadronic model in explaining the extreme HBL nature of the VHE flaring events. We note that when the flaring in VHE was first observed on 2010 March 10 (MJD 56265), the source was in a high-emission state and it continued to be in high-emission state for about a week. Then it started degrading to a low-emission state when the flux was low and the spectrum in zone-1 was almost flat. During the first week of the observation, the transition energy \( E_{\text{trans}} \approx 1 \text{ TeV} \) when the flaring in zone-1 was in a high-emission state. However, from MJD 55272, the transition energy \( E_{\text{trans}} \) started decreasing and reached a minimum value of 0.25 TeV on MJD 55274 and for rest of the days zone-1 was in a low-emission state. The shift in the \( E_{\text{trans}} \) from \( \sim 1 \text{ TeV} \) to \( \lesssim 0.25 \text{ TeV} \) shows that toward the end of the VHE flaring, zone-2 had dominated almost the whole spectrum, implying that the seed photon flux in the SSC region has changed from a flatter behavior (\( \beta_1 \approx 0.7 \)) to a steeper (\( \beta_2 \approx 1.5 \)) one. This change in spectral behavior, in principle, can be detected by simultaneous observation of the SED in the low-energy tail region of the SSC band and in the VHE band during the EHBL-like outburst of the source. We have also estimated the minimum bulk Lorentz factor, obtaining a reasonable value of \( \Gamma \approx 21 \). Further analysis of EHBL and EHBL-like transient behaviors will help solidify the evidence for the two-zone photohadronic origin of these phenomena.

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**References**

Abdo, A. A., Ackermann, M., Aguado, I., et al. 2010, ApJ, 716, 30  
Abdo, A. A., Ackermann, M., Ajello, M., et al. 2011, ApJ, 736, 131  
Abeysekara, A. U., Archambault, S., Archer, A., et al. 2017, ApJ, 834, 2  
Acciari, V. A., Ansoldi, S., Antonelli, L. A., et al. 2019, MNRAS, 490, 2284  
Acciari, V. A., Ansoldi, S., Antonelli, L. A., et al. 2020a, A&A, 638, A14  
Acciari, V. A., Ansoldi, S., Antonelli, L. A., et al. 2020b, ApJS, 247, 16  
Ahn, M. L., Ansoldi, S., Antonelli, L. A., et al. 2017, A&A, 603, A31  
Ahnen, M. L., Ansoldi, S., Antonelli, L. A., et al. 2018, A&A, 620, A181  
Aleksić, J., Ansoldi, S., Antonelli, L. A., et al. 2015a, A&A, 578, A22  
Aleksić, J., Ansoldi, S., Antonelli, L. A., et al. 2015b, A&A, 573, A50  
Amenomori, M., Ayabe, S., Cui, S. W., et al. 2003, ApJ, 598, 242  
Banerjee, B., Joshi, M., Majumdar, P., et al. 2019, MNRAS, 487, 845  
Beck, M., Arbet-Engels, A., Baack, D., et al. 2020, in 36th Int. Cosmic Ray Conf. (ICRC2019) - GRL - Gamma Ray Indirect, 358 (Trieste: PoS), 630  
Blazeykowski, M., Blaylock, G., Bond, I. H., et al. 2005, ApJ, 630, 130  
Blazeykowski, M., Sikora, M., Moderski, R., & Madejski, G. 2000, ApJ, 545, 107  
Böttcher, M., Dermer, C. D., & Finke, J. D. 2008, ApJL, 679, L9  
Cerruti, M., Zech, A., Boisson, C., & Inoue, S. 2015, MNRAS, 448, 910  
Chary, R.-R., & Pope, A. 2010, arXiv:1003.1731  
Costamante, L., Bonnoli, G., Tavecchio, F., et al. 2018, MNRAS, 477, 4257  
Costamante, L., Ghisellini, G., Giommi, P., et al. 2001, A&A, 371, 512  
Cui, W., Blazeykowski, M., Aller, M., et al. 2005, in AIP Conf. Proc. 745, 2nd Int. Symp. on High Energy Gamma-Ray Astronomy, ed. F. A. Aharonian et al. (Melville, NY: AIP), 455  
de León, A. R., Brown, A. M., & Chadwick, P. M. 2021, MNRAS, 501, 2198  
Dermer, C. D., & Schlickeiser, R. 1993, ApJ, 416, 458  
Domínguez, A., Primack, J. R., Rosario, D. J., et al. 2011, MNRAS, 410, 2556  
Fossati, G., Buckley, J. H., Bond, I. H., et al. 2008, ApJ, 677, 906  
Franceschini, A., Rodighiero, G., & Vaccari, M. 2008, A&A, 487, 837  
Gao, H., Lei, W.-H., & Zhang, B. 2013, MNRAS, 435, 2520  
Hauser, M. G., & Dwek, E. 2001, ARA&A, 39, 249  
Inoue, Y., Inoue, S., Kobayashi, M. A. R., et al. 2013, ApJ, 768, 197  
Kaufmann, S., Wagner, S. J., Tibolla, O., & Hauser, M. 2011, A&A, 534, A130  
Krawczynski, H., Hughes, S. B., Horan, D., et al. 2004, ApJ, 601, 151  
Maraschi, L., Ghisellini, G., & Celotti, A. 1992, ApJ, 397, L5  
Mastichiadis, A., Petropoulou, M., & Dimitrakoudis, S. 2013, MNRAS, 434, 2684  
Murase, K., Dermer, C. D., Takami, H., & Migliori, G. 2012, ApJ, 749, 63  
Pichel, A. 2009, arXiv:0908.0010  
Pozzetti, L., & Madau, P. 2001, in IAU Symp. 204, The Extragalactic Infrared Background and its Cosmological Implications (Cambridge: Cambridge Univ. Press), 71  
Punch, M., Ackeroft, C. W., Cawley, M. F., et al. 1992, Natur, 358, 477  
Sahu, S. 2019, RMxP, 65, 307  
Sahu, S., de León, A. R., Nagataki, S., & Gupta, V. 2018, EPJC, 78, 557  
Sahu, S., López Fortín, C., Iglesias Martínez, M., et al. 2020b, MNRAS, 492, 2261  
Sahu, S., López Fortín, C. E., Castañeda Hernández, L. H., Nagataki, S., & Rajpoot, S. 2020a, ApJ, 901, 132  
Sahu, S., López Fortín, C. E., Castañeda Hernández, L. H., Najataki, S., & Rajpoot, S. 2021, ApJ, 906, 91  
Sahu, S., López Fortín, C. E., & Nagataki, S. 2019, ApJL, 884, L17  
Sahu, S., Miranda, L. S., & Rajpoot, S. 2016, EPJC, 76, 127  
Sikora, M., Begelman, M. C., & Rees, M. J. 1994, ApJ, 424, 153  
Stecker, F. W., Malkan, M. A., & Scully, S. T. 2006, ApJ, 648, 774  
Stecker, F. W., Scully, S. T., & Malkan, M. A. 2016, ApJ, 827, 6  
Thiczykunt, M. 2010, in 25th Texas Symp. on Relativistic Astrophysics (Trieste: PoS), 97  
Zech, A., Cerruti, M., & Mazin, D. 2017, A&A, 602, A25  
Zheng, Y. G., Yang, C. Y., Kang, S.-J., & Bai, J. M. 2021, RAA, 21, 008