Mrk 421: The Multi-TeV emission and its astrophysical origin

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Abstract. The TeV blazar Markarian 421 underwent multi-TeV flaring during April 2004 and simultaneously observations in the X-ray and TeV energies were made. It was observed that the TeV outbursts had no counterparts in the lower energy range. One implication of this is that it might be an orphan flare. We show that Fermi-accelerated protons of energy \(\leq 168\) TeV can interact with the low energy tail of the background synchrotron self-Compton photons in the inner region of the blazar to produce the multi-TeV flare and our results fit very well with the observed spectrum.

1. Introduction
Active galactic nuclei (AGN) emit electromagnetic radiation, the spectrum of which stretches from radio to gamma-rays and exhibit large luminosity variations on time scales ranging from less than an hour up to several years. A super massive black hole is believed to sit at the center of the AGN surrounded by an accretion disk in the inner region and a torus of gas cloud in the outer region. Oppositely directed relativistic jets are ejected from the AGN which are perpendicular to the accretion disk and the torus. The spectral energy distribution (SED) of these AGN have a double peak structure in the \(\nu - \nu F_\nu\) plane (frequency vs frequency times flux). In the context of the leptonic model, the low energy peak corresponds to the synchrotron radiation from a population of relativistic electrons in the jet. Although the general consensus is that the high energy peak corresponds to the synchrotron self Compton (SSC) scattering of the high energy electrons with their self-produced synchrotron photons, this result remains inconclusive for various reasons. However, this leptonic model is very successful in explaining the multi wavelength emission from blazars and FR I galaxies\(^[1]\).

Also the inevitable outcome of the leptonic scenario is that, emission in multi-TeV energy has to be accompanied by a simultaneously enhanced emission in the synchrotron peak. Unfortunately the enhanced synchrotron emission was not observed in the flaring of 1ES 1959+650 in June 2002\(^[2]\) and also probably in the flaring of Mrk 421 in April 2004\(^[3]\), which implies that the SSC scenario may not be efficient enough to contribute in the multi-TeV regime.

Previously it was shown that the above hadronic processes are inefficient to explain the multi-TeV emission. However, this problem can be circumvented if one assumes that within the jet there is a dense inner jet region\(^[4]\). The multi-TeV peak can also be produced by pp interactions.
It was shown earlier that normally the \( pp \) process is inefficient to produce \( \gamma \)-rays in the blazar environment unless the jet-cloud interaction is taken into account[5].

2. Photohadronic Model

Sahu et al. [4, 6, 7] have employed the hadronic model to address the orphan TeV flaring of 1ES 1959+650 and the multi-TeV emission from Cen A and M87. Recently this model is also used to make estimates of the neutrinos flux from the TeV-blazars and their spatial correlation with the IceCube events[8]. Here we use the same hadronic model to explain the multi-TeV orphan flaring of Mrk 421. In this model the Fermi-accelerated high energy protons interact with the SSC photons in the core region of the jet. Subsequently the \( \Delta \)-resonance decays to charged and neutral pions as follows,

\[
p + \gamma \rightarrow \Delta^{\pm} \rightarrow \left\{ \begin{array}{ll}
p \pi^0, & n \pi^+ \rightarrow ne^+\nu_\mu\bar{\nu}_\mu, \\
\end{array} \right. \quad (1)
\]

The decay of neutral pions to TeV photons gives the multi-TeV SED. Throughout our work we use natural units \( c = \hbar = 1 \). The \( \pi^0 \)-decay TeV photon energy \( E_\gamma \) and the target SSC photon energy \( \epsilon_\gamma \) in the observer frame are related as follows,

\[
E_\gamma \epsilon_\gamma \simeq 0.032 \frac{D^2}{(1 + z)^2} \text{GeV}^2, \tag{2}
\]

where \( D \) is the Doppler factor and \( z \) is the redshift. The observed TeV \( \gamma \)-ray energy and the proton energy \( E_p \) are related through

\[
E_p = \frac{10\Gamma}{D} E_\gamma, \tag{3}
\]

where \( \Gamma \) is the bulk Lorentz factor of the relativistic jet. These emissions are classified into non-flaring and flaring events where (henceforth \( ' \) implies the jet comoving frame) and satisfying the kinematical conditions in Eq.(2). As discussed in Ref.[4], the flaring occurs within a compact and confined volume of a smaller inner cone which is enclosed in a bigger outer cone. We can express the injected proton spectrum for both non-flaring and flaring processes in a unified manner as[4, 9]

\[
\frac{dN_p}{dE_p} \propto E_p^{-\alpha} \left\{ \begin{array}{ll}
1, & \text{non-flaring} \\
e^{-E_p/E_{p,c}}, & \text{flaring} \\
\end{array} \right. \quad (4)
\]

where \( E_{p,c} \) is the break energy for the high energy protons.

The high energy protons will interact in the flaring region where the comoving photon number density is \( n_\gamma,' \) to produce the \( \Delta \)-resonance. The photon density in the flaring region is much higher than the rest of the blob (non-flaring region with the photon density \( n_\gamma \)) [10]. The optical depth of the \( \Delta \)-resonance process in the inner jet region is given by

\[
\tau_{p\gamma} = n_\gamma,' \sigma_\Delta R_f', \tag{5}
\]

where the \( R_f' \) is the inner blob radius corresponding to the inner jet and the resonant cross section is \( \sigma_\Delta \sim 5 \times 10^{-28} \text{cm}^2 \).

In the inner region we compare the dynamical time scale \( t_d' = R_f' \) with the \( p\gamma \) interaction time scale \( t_{p\gamma}' = (n_\gamma,' \sigma_\Delta K_{p\gamma})^{-1} \) to constraint the seed photon density so that multi-TeV photons can be produced. For a moderate efficiency of this process, we can assume \( t_{p\gamma}' > t_d' \).
and this gives $\tau_{\gamma'\gamma} < 2$, where the inelasticity parameter is assigned the usual value of $K_{\gamma'\gamma} = 0.5$. Also by assuming the Eddington luminosity is equally shared by the jet and the counter jet, the luminosity within the inner region for a seed photon energy $\epsilon_{\gamma}$ will satisfy $(4\pi n'_{\gamma,f} R_{f}^{2} \epsilon'_{\gamma}) \ll L_{\text{Edd}}/2$. This puts an upper limit on the seed photon density as

$$n'_{\gamma,f} \ll \frac{L_{\text{Edd}}}{8\pi R_{f}^{2} \epsilon_{\gamma}}. \quad (6)$$

We simply assume the scaling behavior of the photon densities in different background energies as follows:

$$\frac{n'_{\gamma,f}(\epsilon_{\gamma1})}{n'_{\gamma,f}(\epsilon_{\gamma2})} = \frac{n'_{\gamma1}(\epsilon_{\gamma1})}{n'_{\gamma2}(\epsilon_{\gamma2})}. \quad (7)$$

This implies that, the ratio of photon densities at two different background energies $\epsilon_{\gamma1}$ and $\epsilon_{\gamma2}$ in the flaring and the non-flaring states remains the same. The photon density in the outer region is calculated from the observed flux in the usual way. In the photohadronic scenario, the number of $\pi^{0}$-decay photons at a given energy is proportional to both the number of high energy protons and the density of the SSC background photons in the jet, i.e. $N(E_{\pi^{0}}) \propto N(E_{p})n'_{\gamma}$. For the flaring case $n'_{\gamma}$ is replaced by the photon density in the flaring region ($n'_{\gamma,f}$). The $\gamma$-ray flux from the $\pi^{0}$ decay is deduced to be

$$F_{\gamma}(E_{\gamma}) \equiv \frac{E_{\gamma}^{2} dN(E_{\gamma})}{dE_{\gamma}} \propto \frac{E_{p}^{2} dN(E_{p})}{dE_{p}} - n'_{\gamma,f}. \quad (8)$$

Using the scaling behavior of Eq.(7), the observed multi-TeV photon flux from $\pi^{0}$-decay at two different observed photon energies $E_{\gamma1}$ and $E_{\gamma2}$ can be expressed as

$$\frac{F_{\gamma}(E_{\gamma1})}{F_{\gamma}(E_{\gamma2})} = \frac{n'_{\gamma1}(\epsilon_{\gamma1})}{n'_{\gamma2}(\epsilon_{\gamma2})} \left( \frac{E_{\gamma1}}{E_{\gamma2}} \right)^{-\alpha+2} e^{-(E_{\gamma1}-E_{\gamma2})/E_{c}}, \quad (9)$$

where $E_{\gamma1,2}$ correspond to the photon energy $E_{p1,2}$. In this derivation we have used the relations $E_{p1}/E_{p2} = E_{\gamma1}/E_{\gamma2}$, and $E_{p1,2}/E_{p,c} = E_{\gamma1,2}/E_{c}$, where $E_{c}$ is the $\gamma$-ray cut-off energy corresponding to $E_{p,c}$. By using the known flux at a particular energy in the flaring/non-flaring state, we can calculate the flux at other energies using Eq.(9). The normalization constant can also be calculated.

In terms of SSC photon energy and its luminosity, the photon number density $n'_{\gamma}$ is expressed as

$$n'_{\gamma}(\epsilon_{\gamma}) = \eta \frac{L_{\gamma,\text{SSC}}(1+z)}{D^{2+\kappa}4\pi R_{b}^{2}\epsilon_{\gamma}}, \quad (10)$$

where $\eta$ is the efficiency of SSC process and $\kappa$ describes whether the jet is continuous ($\kappa = 0$) or discrete ($\kappa = 1$). In this work we take $\eta = 1$ for 100% efficiency. The SSC photon luminosity is expressed in terms of the observed flux ($\Phi_{\text{SSC}}(\epsilon_{\gamma}) = \epsilon_{\gamma}^{2}dN_{\gamma}/d\epsilon_{\gamma}$) and is given by

$$L_{\gamma,\text{SSC}} = 4\pi d_{L}^{2} \Phi_{\text{SSC}}(\epsilon_{\gamma}) \frac{(1+z)^{2}}{(1+z)^{2}}. \quad (11)$$

Furthermore, by using Eq.(2), we can simplify the ratio of photon densities given in Eq.(7) to

$$\frac{n'_{\gamma1}(\epsilon_{\gamma1})}{n'_{\gamma2}(\epsilon_{\gamma2})} = \frac{\Phi_{\text{SSC}}(\epsilon_{\gamma1}) E_{\gamma1}}{\Phi_{\text{SSC}}(\epsilon_{\gamma2}) E_{\gamma2}}. \quad (12)$$
Here we take $\kappa = 0$ as representative value for the calculation of $n_p'$. We note that $\kappa = 1$ will only lead to the suppression of the photon number density for the outer enveloping jet without changing the main conclusions of our work. This follows from Eq.(12) where proportionality factors depending on $\kappa$ cancel out. Eq.(9) in terms of observed SSC flux and $E_\gamma$ takes the following form,

$$
\frac{F_\gamma(E_{\gamma 1})}{F_\gamma(E_{\gamma 2})} = \frac{\Phi_{SSC}(\epsilon_{\gamma 1})}{\Phi_{SSC}(\epsilon_{\gamma 2})} \left( \frac{E_{\gamma 1}}{E_{\gamma 2}} \right)^{-\alpha + 3} e^{-(E_{\gamma 1} - E_{\gamma 2})/E_c},
$$

and uses the SED of SSC photon calculated using the leptonic model. Here the multi-TeV flux is proportional to $E_\gamma^{-\alpha + 3}$ and $\Phi_{SSC}(\epsilon_\gamma)$ while in Eq.(9) it is proportional to $E_\gamma^{-\alpha + 2}$ and to the photon number density $n_p'(\epsilon_\gamma)$. In the photohadronic process ($p\gamma$), the multi-TeV photon flux is expressed as

$$
F(E_\gamma) = A_\gamma \Phi_{SSC}(\epsilon_\gamma) \left( \frac{E_\gamma}{\text{TeV}} \right)^{-\alpha + 3} e^{-E_\gamma/E_c}.
$$

Both $\epsilon_\gamma$ and $E_\gamma$ satisfy the condition given in Eq.(2) and the dimensionless constant $A_\gamma$ is given by

$$
A_\gamma = \frac{F(E_{\gamma 2})}{\Phi_{SSC}(\epsilon_{\gamma 2})} \left( \frac{\text{TeV}}{E_{\gamma 2}} \right)^{-\alpha + 3} e^{E_{\gamma 2}/E_c}.
$$

Eq.(14) will be used to calculate the multi-TeV flux from both non-flaring (without exponential decay term) and flaring events from AGN and their subclasses if the emission is due to photohadronic process from the core region. We can calculate the Fermi accelerated high energy proton flux $F_p$ from the TeV $\gamma$-ray flux through the relation

$$
F_p(E_p) = 7.5 \times \frac{F_{\gamma}(E_{\gamma})}{\tau_{p\gamma}(E_p)}.
$$

The optical depth $\tau_{p\gamma}$ is given in Eq.(5). For the observed highest energy proton energy $E_p$, $F_p(E_p)$ will always be smaller than the Eddington flux $F_{Edd}$. This condition puts a lower limit on the optical depth of the process and is given by

$$
\tau_{p\gamma}(E_p) > 7.5 \times \frac{F_{\gamma}(E_{\gamma})}{F_{Edd}}.
$$

From the comparison of different time scales and from Eq.(17) we will be able to constraint the seed photon density in the inner jet region.

3. Results

The flaring of Mrk 421 in April 2004 was observed in the energy range $0.25 \text{TeV}(6.0 \times 10^{25} \text{Hz}) \leq E_\gamma \leq 16.85 \text{TeV}(4.1 \times 10^{27} \text{Hz})$ by the Whipple telescope. In the hadronic model alluded to previously, this corresponds to the Fermi accelerated proton energy in the range $2.5 \text{TeV} \leq E_p \leq 168 \text{TeV}$ and the corresponding background photon energy will lie in the range $23.6 \text{MeV}(5.7 \times 10^{21} \text{Hz}) \geq \epsilon_\gamma \geq 0.35 \text{MeV}(8.4 \times 10^{10} \text{Hz})$. This range of $\epsilon_\gamma$ is the shaded region shown in Fig. 1 which is in the low energy tail of the SSC photons. For the calculation of the normalized multi-TeV flux we take into account one of the observed TeV fluxes from the flare at its corresponding energy. In this model the free parameters are the spectral index $\alpha$ and the TeV $\gamma$-ray cut-off energy $E_c$. The best fit is obtained for the values $\alpha = 2.7$ and $E_c = 6.2 \text{TeV}$. This value of $E_c$ corresponds to the proton cut-off energy $E_{p,c} = 62 \text{TeV}$ and the SSC photon energy $\epsilon_{\gamma,\text{SSC}} = 0.96 \text{MeV}(2.3 \times 10^{20} \text{Hz})$ which is very close to the beginning of the SSC energy as shown in Fig. 1. This shows that for orphan flaring, the cut-off energy $E_c$ is due to the change from the synchrotron band to the SSC band and can be calculated from their crossover energy.
Figure 1. The SED of Mrk 421 is shown in all the energy bands (the leptonic model part in blue line) which are taken from Ref.[3]. The flare of April 2004 in multi-TeV energy is shown here. The hadronic model fit to the April 2004 data is shown as continuous line to the extreme right. The shaded region is the energy range of SSC photons where the Fermi-accelerated protons collide to produce the ∆-resonance.

Figure 2. The continuous curve is the hadronic model fit to the multi-TeV flaring data of Mrk 421.

region. In Fig. 2 we show the observed multi-TeV SED and the predictions of our model. In our results, the presence of $\Phi_{SSC}(\epsilon_\gamma)$ in Eq.(14) modifies the power-law with the exponential fall-off scenario. From the best fit parameters we obtain the value of the dimensionless constant $A_\gamma \simeq 20$ in Eq. (15).

In the flaring state, as has been alluded to before, in general, the flux of the two opposing jets can be as high as $F_{Edd}/2$. However, the highest energy protons with $E_p = 168$ TeV must have flux $F_p < F_{Edd}/2$. Using Eq.(16) this constraint translates into $\tau_{\gamma\gamma} > 0.02$ which corresponds to $n_{\gamma,f}^\prime > 1.3 \times 10^{10}$ cm$^{-3}$ in the inner jet. However, the hidden jet lies between $R_s$ and $R_b^\prime$. As one representative value we take $R_b^\prime \simeq 3 \times 10^{15}$. From Eq.(6) the seed photon density for $\epsilon_\gamma = 0.35$ MeV satisfies the inequality $n_{\gamma,f}^\prime < 8.9 \times 10^{10}$ cm$^{-3}$ which translates to the optical
depth to be constrained as $\tau_{\gamma\gamma} < 0.13$. The upshot of all this is that while the value of $\tau_{\gamma\gamma} < 2$ is a generic constraint, a more refined present analysis constrains the optical depth to lie in the range $0.02 < \tau_{\gamma\gamma} < 0.13$. From this the constraint on the photon number density in the inner jet region is determined to be $1.3 \times 10^{10} cm^{-3} < n'_{\gamma,j} < 8.9 \times 10^{10} cm^{-3}$, which shows that the photon density in this region is high. Due to the adiabatic expansion of the inner blob, the photon density will be reduced to $n'_\gamma$ and the energy will dissipate once these photons cross into the bigger outer cone. In spite of the two-zones structure, only the outer zone will be responsible for the observed synchrotron and the IC peaks. From the leptonic model fit to the SED, the magnetic field in the outer jet region is determined to be $B' = 0.26 G$. In general, higher values of the magnetic field are expected to be present in the inner jet region. The maximum proton energy in the hidden jet region will be $E_{p,\text{max}} \sim 10^{18}(B'/1G) eV$ and for larger magnetic fields, $E_{p,\text{max}}$ can even be higher. In comparison, in the non-flaring jet scenario case we estimate the proton flux needed to explain the observed TeV $\gamma$-rays as follows: Corresponding to the seed photon energy $\epsilon_\gamma = 0.35$ MeV, the photon density and the optical depth are respectively $n'_\gamma \sim 4 \times 10^3 cm^{-3}$ and $\tau_{\gamma\gamma} \sim 1.4 \times 10^{-8}$. This corresponds to the observed TeV photon energy $E'_\gamma = 16.8$ TeV and the proton energy $E_p = 168$ TeV respectively. The high energy $\gamma$-ray flux for $E'_\gamma = 16.8$ TeV is $F'_\gamma \sim 3.16 \times 10^{-11} erg cm^{-2}s^{-1}$. Using Eq.(16) we obtain the high energy proton flux as $F_p \simeq 10^6 \times F_{E,\text{ed}}$. This shows that the normal jet model needs super Eddington power in the protons to explain the high energy peak, whereas our inner jet scenario eliminates this extreme energy requirement.

In passing we note that, in the energy range considered, the high energy protons will be accompanied by high energy electrons. These electrons will emit synchrotron photons in the energy range $4 \times 10^{19} Hz$ to $2 \times 10^{20}$ Hz when encountering the magnetic field of the jet. These energy range photons lie in the lower part of the SSC spectrum and thus will not be observed due to their flux being low. The high energy electrons will also emit SSC photons and their energy is given by $E_{IC} \sim \gamma^2 e_{\text{syn}}$. By considering the electron Lorentz factor in the range $7 \times 10^2 \leq \gamma_e \leq 4 \times 10^4$ and the peak energy of the synchrotron photons to be $e_{\text{syn}} \sim 10^{18} Hz$, we determine the SSC process contribution to the flux in the energy range $2 GeV \leq E_{IC} \leq 6.6 TeV$. The details of the SSC flux depend on the breaks in SSC spectrum and the spectral index. It is observed that during the flaring of Mrk 421, the X-ray emission reached the peak days after the TeV emission, which poses a serious challenge to the SSC model.[3].

The multi-TeV photons in the energy range $0.25 TeV \leq E_\gamma \leq 16.8 TeV$ can interact with the background photons to produce $e^+ e^-$ pairs in which the individual electrons or positrons have energy $E_\gamma/2$. To produce the $e^+e^-$ pair, the required threshold seed photon energy of $\epsilon_\gamma \geq 2m_e^2/E_\gamma$ is needed. During the flaring, multi-TeV $\gamma$-rays will interact with soft seed photons in the energy range $0.05 eV \leq \epsilon_\gamma \leq 3.5 eV$ (in between the infrared and the visible range), where $\sigma_{\gamma\gamma} \sim 1.7 \times 10^{-25} cm^2$ is the maximum cross section. For higher $\epsilon_\gamma$, $\sigma_{\gamma\gamma}$ will be smaller. We consider the sources of these soft photons to be from the synchrotron emission of 1 to 10 GeV electrons interacting with the magnetic field $B \sim 1$ Gauss and the flux of the ambient photons coming from the disk. On the other hand the multi-TeV $\gamma$-rays are produced beyond this region where the photons make the low energy tail ($0.35$ $MeV - 23.5$ $MeV$ range) of the IC photons. The regions $0.05$ $eV - 3.5$ $eV$ and $0.35$ $MeV - 23.5$ $MeV$ represent two distinct energy ranges. The TeV photons will mostly encounter the tail region of the SSC spectrum. The pair production cross section for $e_\gamma \geq 0.35$ $MeV$ is very small $\sigma_{\gamma\gamma} \leq 10^{-30}$ cm$^2$, which corresponds to a mean free path of $\lambda_{\gamma\gamma} \geq 10^{19}$ cm. Hence, the TeV photons will not be attenuated much due to the $e^+ e^-$ pair production. Also it has been observed that, during the flaring of Mrk 421, the variation in the light curves at optical and radio wavelengths are minimal.[3], which implies that the low energy photon production was suppressed. In addition to the above scenario, the positrons produced from the $\pi^+$ decay have energy $E_\gamma/2$ and will radiate synchrotron photons in the energy range $2 \times 10^{17}$ Hz to $9 \times 10^{20}$ Hz. The photon flux
$F_{e^+_{\text{syn}}}$ from the synchrotron radiation of $e^+$ will be much smaller than $F_\gamma(E_\gamma = 0.25 \, \text{TeV}) / 8$, i.e., $F_{e^+_{\text{syn}}} \ll 8 \times 10^{-11} \, \text{erg cm}^{-2} \text{s}^{-1}$. From the above analysis our conclusion is that the photon fluxes from the synchrotron emission of the electrons and positrons are not observable during the flaring event of Mrk 421 in April 2004. This situation is very much like the one discussed in the orphan flaring of 1ES 1959+650. Hence we conclude that the flaring of Mrk 421 is orphan in nature. In principle, the flux of multi-TeV $\gamma$-rays from the extragalactic sources is attenuated due to interactions with the diffuse extragalactic background light (EBL) through the process $\gamma_{\text{TeV}} + \gamma_b \rightarrow e^+e^-$ due to the energy dependent optical depth. But for low redshifts and the energy range of our interest, the optical depth $\tau_{\gamma\gamma}$ does not vary much. Hence we can assume an almost constant optical depth$[9]$ so that the spectral shape remains nearly unchanged.

4. Conclusions

We conclude that the orphan flaring of Mrk 421 can be explained well by the photohadronic model$[11]$. We observe that, in this model, the multi-TeV photon flux is proportional to $\Phi_{\text{SSC}}(E_\gamma) E_\gamma^{-\alpha + 3}$ supplemented with an exponential decay term as shown in Eq. (14). This implies that the Fermi accelerated protons interact with the background photons (in the low energy tail) of the SSC spectrum. In the present work we have shown that the higher photon density in the internal jet scenario eliminates the requirement of the super Eddington luminosity to explain the multi-TeV emission. During the April 2004 flaring of Mrk 421, we have demonstrated that the flux from the synchrotron emission from the high energy $e^+$ and $e^-$ is suppressed relative to the normal flux, implying that the flaring was orphan in nature, like the one observed in 1ES 1959+650.

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