Modelling the very high energy flare of 3C 279 using one-zone leptonic model

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ABSTRACT

We model the simultaneous observations of the flat-spectrum radio quasar 3C 279 at radio, optical, X-ray and very high energy (VHE) gamma-ray energies during 2006 flare using a simple one-zone leptonic model. We consider synchrotron emission due to cooling of a non-thermal electron distribution in an equipartition magnetic field and inverse Compton emission due to the scattering of synchrotron photons (SSC) and external soft photons (EC) by the same distribution of electrons. We show that the VHE gamma-ray flux cannot be explained by an SSC process thereby suggesting the EC mechanism as a plausible emission process at this energy. The EC scattering of broad-line region photons to very high energies will be in the Klein–Nishina regime predicting a steep spectrum which is contrary to the observations. However, the infrared photons from the dusty torus can be boosted to very high energies with the scattering process remaining in the Thomson regime. Though the EC process can successfully explain the observed VHE flux, it requires a magnetic field much lower than the equipartition value to reproduce the observed X-ray flux. Hence, we attribute the X-ray emission to the SSC process. We derive the physical parameters of 3C 279 considering the above-mentioned emission processes. In addition, we assume the size of the emission region constrained by a variability time-scale of one day. This model can successfully reproduce the broad-band spectrum of 3C 279 but predicts substantially large flux at MeV–GeV energies.

Key words: radiation mechanisms: non-thermal – galaxies: active – galaxies: jets – quasars: individual: 3C 279.

1 INTRODUCTION

Flat-spectrum radio quasars (FSRQ) are radio-loud active galactic nuclei (AGN) with broad emission lines and a non-thermal spectrum extending from radio to gamma-ray energies. They are characterized by luminous core, rapidly variable non-thermal emission, high radio and optical polarization, flat-spectrum radio emission and/or superluminal motion. Similar properties are also observed in BL Lacs and these two types of AGN are classified as blazars. According to the AGN unification scheme, blazars are the class of AGN with a relativistic jet pointed close to the line of sight of the observer (Urry & Padovani 1995). The spectral energy distribution (SED) of FSRQ is characterized by two broad humps. The low-energy hump in the SED is well understood as synchrotron emission from a relativistic distribution of electrons, whereas the origin of high-energy hump is still a matter of debate. There are several models to explain the high-energy emission based on either leptonic or hadronic interactions (Blandford & Levinson 1995; Bloom & Marscher 1996; Mannheim 1998; Aharonian et al. 2000; Pohl & Schlickeiser 2000). Under the assumption of leptonic models, high-energy emission is explained via inverse Compton scattering of soft target photons. The target photons can be the synchrotron photons [synchrotron self-Compton (SSC)] (Konigl 1981; Marscher & Gear 1985; Ghisellini & Marscher 1989) or the photons external to the jet [external Compton (EC)] (Begelman & Sikora 1987; Melia & Konigl 1989; Dermer, Schlickeiser & Mastichiadis 1992). These external photons can be the accretion disc photons (Dermer & Schlickeiser 1993; Boettcher, Mause & Schlickeiser 1997) or the accretion disc photons reprocessed by broad-line region (BLR) clouds (Sikora, Begelman & Rees 1994; Ghisellini & Madau 1996) or the infrared (IR) radiation from the dusty torus (Sikora et al. 1994; Blažejowski et al. 2000; Ghisellini & Tavecchio 2008). Hadronic models explain the high-energy emission as an outcome of the synchrotron proton emission and proton–photon interactions with the synchrotron photons (synchrotron proton blazar model) (Mannheim 1998; Mücke et al. 2003; Böttcher, Reimer & Marscher 2009).

3C 279 ($z = 0.536$) is a well-studied source at various energy bands with several simultaneous multiwavelength campaigns (Maraschi et al. 1994; Hartman et al. 1996; Wehrle et al. 1998;
It was the first blazar observed at gamma-ray energies by the satellite-based experiment EGRET (Energetic Gamma-Ray Experiment Telescope) (Hartman et al. 1992) and the first FSRQ to be detected at GeV–TeV [very high energy (VHE)] gamma-ray energies by the ground-based atmospheric Cherenkov experiment MAGIC (Major Atmospheric Gamma-Ray Imaging Cherenkov) (Albert et al. 2008). The flux of 3C 279 is also known to be strongly variable at radio, IR, optical, ultraviolet, X-ray and gamma-ray energies (Makino et al. 1989, and references therein). During 2006, 3C 279 underwent a dramatic flare and was observed by the Whole Earth Blazar Telescope (WEBT) campaign (Böttcher et al. 2007) at radio, near-IR and optical frequencies and simultaneously monitored by Rossi X-ray Timing Explorer (RXTE) at X-ray energies (Chatterjee et al. 2008) and by MAGIC telescope at VHE gamma-rays (Albert et al. 2008).

The SED of 3C 279 is modelled as synchrotron and inverse Compton emission using these simultaneous observations at various energies. The explanation of the Compton hump as an outcome of the SSC process due to the cooling of a relativistic power-law electron distribution is not very successful (Böttcher et al. 2009). This interpretation had a serious drawback in explaining the high-energy gamma-ray (~ 1 GeV) detection from 3C 279 since it requires very high radiation energy density compared to magnetic energy density (Maraschi, Ghisellini & Celotti 1992). It also requires unusually low magnetic field to explain the VHE emission (Böttcher et al. 2009). However, in case of BL Lac objects, the models considering the SSC process are able to reproduce gamma-ray emission successfully (Stecker, de Jager & Salomon 1996; Coppi & Aharonian 1999; Bhattacharya, Sahayanathan & Bhattacharyya, 2005). Other alternative explanation for the Compton hump of 3C 279 is the EC mechanism with the target photons external to the jet. Target photons from the accretion disc will be strongly deboosted due to the high Lorentz factor of the jet (Γ ~ 10–25) and may not play an important role [however see Boettcher et al. (1997) for an alternative]. The photons from BLR clouds cannot be boosted to VHE gamma-rays since the scattering of Lyman α line emission [the dominant emission from BLR clouds (Francis et al. 1991)] will result in the Klein–Nishina regime (Ghisellini & Tavecchio 2009; Section 3.2) predicting a steep spectrum contrary to the observed hard spectrum. The third option, IR photons from the dusty torus, can be a plausible candidate for the target photons in the EC process since the scattering of these photons to VHE gamma-ray energies will still be in the Thomson regime (Ghisellini & Tavecchio 2009; Section 3.2). The importance of Compton scattering of IR photons from dusty torus was first studied in detail by Blazekowski et al. (2000) to explain high-energy gamma-rays detected by EGRET. Though the EC process is widely accepted to explain the gamma-ray emission of 3C 279, Lindfors, Valtala & Türl (2005) argue in favour of the SSC mechanism based on observed radio–gamma-ray correlation and the quadratic dependence of the synchrotron and inverse Compton peak fluxes during the flare.

In this paper, we use the simultaneous observation of 3C 279 at radio, near-IR, optical, X-ray and VHE gamma-ray energies (Böttcher et al. 2007; Albert et al. 2008; Chatterjee et al. 2008) to deduce the physical parameters of the source. We consider synchrotron, SSC and EC emission from a power-law distribution of electrons. We assume a magnetic field which is in equipartition with the particle energy. In the next section we outline the model and in Section 3 we show the plausible target photons for the inverse Compton process to explain the observed flux at different energy bands. In Section 4 we present the estimated physical parameters of 3C 279 and discuss implications of the present model and the results. A cosmology with Ωm = 0.3, ΩΛ = 0.7 and H0 = 70 km s^{-1} Mpc^{-1} is used in this work.

2 MODEL

We assume the emission region to be a spherical blob moving down the jet at relativistic speed with the Lorentz factor Γ. Since the jets of blazars are aligned towards the line of sight of the observer, we assume the Doppler factor δ ≈ Γ. The radiation from the emission region is due to synchrotron and inverse Compton cooling of relativistic electrons described by a broken power-law distribution (quantities with prime are measured at the rest frame of the emission region):

\[ N'(\gamma')d\gamma' = \left\{ \begin{array}{ll} K\gamma'^p d\gamma', & \gamma'_\text{min} < \gamma' < \gamma'_b \\ K\gamma'^{-q} d\gamma', & \gamma'_b < \gamma' < \gamma'_\text{max} \end{array} \right. \]

where \( \gamma' \) is the Lorentz factor of the electron, \( p \) and \( q \) are the power-law indices before and after the break corresponding to the Lorentz factor \( \gamma'_b \) and \( K \) is the particle normalization. In the blob frame, protons are assumed to be cold and contribute only to the inertia of the jet. The emission region is permeated with tangled magnetic field \( B \). If we assume the equipartition condition between the magnetic field energy density \( U_B \) and the particle energy density, then the equipartition magnetic field \( B_{eq} \) will satisfy

\[ U_B = \frac{B^2}{8\pi} = mc^2 \int_{\gamma'_\text{min}}^{\gamma'_\text{max}} \gamma' N'(\gamma')d\gamma', \]

where \( m \) is the electron rest mass and \( c \) is the velocity of light. We neglect the contribution of protons in equation (2) due to the assumption that they are cold and do not contribute to the particle energy density. The size of the emission region \( R' \) can be approximated from the observed variability time-scale \( t_{var} \) as

\[ R' \approx \frac{\delta}{1 + z} c t_{var}, \]

where \( z \) is the redshift of the source.

3 INVERSE COMPTON PROCESS IN 3C 279

The radio-to-optical emission of 3C 279 is considered to be synchrotron emission and X-ray-to-γ-ray emission is produced by inverse Compton scattering of soft photons. The soft target photons can be the synchrotron photon itself (SSC) and/or the photon field external to the jet (EC).

3.1 Synchrotron self-Compton

In the SSC mechanism, the synchrotron photons are boosted to high energies via inverse Compton scattering by the same electron distribution responsible for the synchrotron emission itself. An approximate expression for synchrotron emissivity \( \epsilon'_{ss}(\nu') \) (erg cm^{-3} s^{-1} Sr^{-1} Hz^{-1}) due to an electron distribution \( N'(\gamma') \) can be obtained by describing the single particle emissivity in terms of a delta function \( \delta(\nu' - \nu'^2 v_L) \) (Shu 1991; Appendix A),

\[ \epsilon'_{ss}(\nu') \approx \frac{\sigma_T C^2 B^2}{48\pi^2} \nu' V_L^{-3/2} N \left( \frac{\nu'}{V_L} \right) \nu'^{1/2}, \]

where \( \sigma_T \) is Thomson cross-section, \( v_L = eB/(2\pi mc) \) is the Larmor frequency and \( \nu' \) is the frequency of the emitted photon in the rest frame of the emission region. The observed flux
\[ F_{\text{syn}}(v) = \frac{\delta^3(1 + z)}{d_L^2} V' \epsilon_{\text{syn}}' \left( \frac{1 + z}{\delta} \right)^3, \]

where \( V' \) is the volume of the emission region and \( d_L \) is the luminosity distance. The rising part of the observed synchrotron flux in the SED due to the particle distribution given by equation (1) can then be written as

\[ F_{\text{syn}}(v) \approx s(z, p) \delta^{(p+5)/2} B^{(p+1)/2} K^{(p-1)/2} \times \gamma^{(p-1)/2} \text{Jy} \]

for \( v < \delta y_b^2 v_L/(1 + z) \). Here \( s(z, p) \) is a function of \( p \) and \( z \). For \( z = 0.536 \) and \( p = 2.02 \) (corresponding to a radio spectral index 0.51), \( s = 1.7 \times 10^{-42} \).

The observed synchrotron and SSC frequency corresponding to the peak flux in the SED can be approximated as

\[ v_{p,\text{syn}} \approx \frac{\delta}{(1 + z)} y_b^2 v_L, \]

\[ v_{p,\text{ssc}} \approx \frac{\delta}{(1 + z)} y_b^4 v_L. \]

From equations (7) and (8), we get

\[ \gamma_b = \sqrt{\frac{v_{p,\text{ssc}}}{v_{p,\text{syn}}}}. \]

Using equations (2), (3), (6) and (9) (for \( p = 2.02 \)), we get

\[ v_{p,\text{ssc}} \approx 1.53 \times 10^{10} \left( \frac{F_{\text{syn}(\nu)} / 8 \text{Jy}}{2.2 \times 10^{13} \text{Hz}} \right)^{0.28} \left( \frac{v_{\text{tot}}}{1 \text{d}} \right)^{0.85} \times \frac{2}{\nu_{p,\text{syn}}} \left( \frac{v}{3 \times 10^{11} \text{Hz}} \right)^{-0.51} \text{Hz}. \]

However, the gamma-ray peak frequency expressed in equation (10) is too low to interpret the observed VHE flux as an outcome of the SSC mechanism (see Fig. 1).

The emissivity due to the SSC mechanism \( \epsilon_{\text{ssc}}(\nu') \) (erg cm\(^{-3}\) s\(^{-1}\) Hz\(^{-1}\)) for the particle distribution given by equation (1) can be approximated as (Appendix B)

\[ \epsilon_{\text{ssc}}(\nu') \approx \frac{R c}{\delta \nu_b^2} K^2 \sigma_T^2 B^2 v_{\text{L}}^{-3/2} v'^{1/2} f(\nu'). \]

The function \( f(\nu') \) is given by

\[ f(\nu') = \left( \frac{\nu'}{v_L} \right)^{-p/2} \ln \left( \frac{\nu_1}{\nu_2} \right) + \frac{\nu_{\text{q-p}}}{q} \left( \frac{\nu'}{v_L} \right)^{1-q/2} \times \left( \frac{\nu_{\text{q-p}}}{\nu_{\text{min}}} - \frac{\nu_{\text{q-p}}}{\nu_{\text{min}}} \right) \Theta \left( \nu' - \nu_1 \right) \]

\[ + \left( \frac{\nu_{\text{q-p}}}{\nu_L} \right)^{-q/2} \ln \left( \frac{\nu_1}{\nu_2} \right) + \frac{\nu_{\text{q-p}}}{q} \left( \frac{\nu'}{v_L} \right)^{-p/2} \times \left( \frac{\nu_1}{\nu_{\text{max}}} \right) \Theta \left( \nu' - \nu_1 \right) \]

\[ \times \left( \frac{\nu_{\text{q-p}}}{\nu_{\text{max}}} - \frac{\nu_{\text{q-p}}}{\nu_{\text{max}}} \right) \Theta \left( \nu' - \nu_1 \right), \]

where \( \Theta \) is the Heaviside function and

\[ \gamma'_1 = \text{MAX} \left( \frac{\nu_{\text{min}}^{'}}{\nu_b}, \frac{\nu'}{v_L} \right), \]

\[ \gamma'_2 = \text{MIN} \left( \frac{\nu_{\text{min}}^{'}}{\nu_b}, \frac{\nu'}{v_L} \right). \]

The observed SSC flux can be obtained following equation (5) by replacing \( \epsilon_{\text{syn}}(\nu') \) with \( \epsilon_{\text{ssc}}(\nu') \). It should be noted here in deriving equations (12)–(16) that we have assumed the scattering in the Thomson regime. However, at very high energies this may not be valid since the Klein–Nishina effect will be more prominent and should be included (Tavecchio, Maraschi & Ghisellini 1998).

### 3.2 External Compton

In the EC mechanism the target photons for the inverse Compton scattering are accretion disc photons, reprocessed disc photons by the BLR clouds and IR photons from the dusty torus. In the following discussion we consider photons from the BLR clouds and the dusty torus only, since the photons from the accretion disc will be strongly redshifted.

If the VHE emission is produced due to inverse Compton scattering happening in the Klein–Nishina regime, then the VHE spectrum should be steeper than the observed synchrotron spectrum. However, the intrinsic VHE spectrum of 3C 279 is substantially harder after correction for the absorption effects due to extragalactic background light (EBL; Albert et al. 2008) through the considered EBL model (Primack, Bullock & Somerville 2005) is debatable (Stecker & Scully 2009). Therefore, from the inferred intrinsic VHE
spectrum, one can conclude that the scattering process must be in the Thomson regime.

Ghisellini & Tavecchio (2009) showed that the scattering of BLR photons to very high energies will be in the Klein–Nishina regime. The condition for Thomson scattering is given by

\[
\gamma \frac{\nu v^*_0^2}{mc^2} < 1, \quad (17)
\]

where \( h \) is the Planck constant and \( v^*_0 \) is the frequency of the target photon in the AGN frame (quantities with star are measured at the AGN frame). The frequency of the scattered photon in the observer’s frame is

\[
v \approx \frac{\Gamma^2 \gamma^2 v^*_0}{(1 + z)} \quad (18)
\]

From equations (17) and (18) we get

\[
v^*_0 < \frac{1}{\nu(1 + z)} \left( \frac{mc^2}{h} \right)^2 \sim 10^{12} \left( \frac{\nu}{10^{26}} \right)^{-1} \text{Hz}. \quad (19)
\]

The dominant emission from the BLR region is the line emission at 2.47 \( \times \) 10^{13} Hz corresponding to Lyman \( \alpha \) (Francis et al. 1991) and hence the scattering will be in the Klein–Nishina regime. However, the scattering of the IR photon (10^{12}–10^{14} Hz) from the dusty torus to very high energies can still remain in the Thomson regime. The interpretation of VHE emission as a result of inverse Compton scattering of IR photons is also used to explain the VHE emission from the intermediate BL Lac objects, W Comae and 3C 66A, detected by VERITAS (Acciari et al. 2008; Abdo et al. 2011).

The EC emissivity \( \epsilon_\text{ec}(\nu’) \) (erg cm^{-3} s^{-1} \text{Sr}^{-1} Hz^{-1}) due to scattering of an isotropic monoenergetic photon field of frequency \( \nu’ \) and energy density \( \nu’ \) (in the lab frame) can be approximated as (Dermer 1995)

\[
\epsilon_\text{ec}(\nu’) \approx \frac{c \Gamma \nu}{\nu’} N’ \left[ \frac{\nu’}{\Gamma \nu} \right]^{1/2}. \quad (20)
\]

The observed EC flux can be obtained following equation (5) by replacing \( \nu’(\nu’') \) with \( \epsilon_\text{ec}(\nu’) \).

If the observed Compton flux can be represented by a broken power law

\[
F_{\nu, \text{ec}}(\nu) \propto \begin{cases} 
\nu^{-\alpha}, & \nu < \nu_{p, \text{ec}} \\
\nu_{p, \text{ec}}^{\alpha - \beta}, & \nu > \nu_{p, \text{ec}}
\end{cases}, \quad (21)
\]

with \( \alpha = (p - 1)/2 \) and \( \beta = (q - 1)/2 \), then the peak Compton frequency in SED will be

\[
\nu_{p, \text{ec}} = \left( \frac{F_{\nu, \text{ec}}(\nu_{1})}{F_{\nu, \text{ec}}(\nu_{2})} \right)^{1/(\alpha - \beta)}, \quad (22)
\]

where \( \nu_{1} < \nu_{p, \text{ec}} \) and \( \nu_{2} > \nu_{p, \text{ec}} \). Since \( \nu_{p, \text{ec}} \) corresponds to the scattering of the target photon by the particle of energy \( \gamma_{0} mc^2 \), we can write

\[
\nu_{p, \text{ec}} \approx \frac{\Gamma^2}{(1 + z)^2} \gamma_{0} mc^2. \quad (23)
\]

If we assume that both the X-ray and the VHE emission are produced by the EC scattering of IR photons themselves, then using equations (7), (22) and (23), we can write

\[
B \approx 5.4 \times 10^{-2} \left( \frac{\Gamma}{26} \right)^{-1.85} \left( \frac{\nu^*}{5 \times 10^{13}} \right)^{0.28} \left( \frac{t_{\text{var}}}{1 \text{ d}} \right)^{-0.85} \times \left( \frac{\nu_{\text{min}}}{40} \right)^{-0.006} \left( \frac{\nu}{3 \times 10^{11} \text{Hz}} \right)^{0.15} \text{G}. \quad (24)
\]

Here we have used \( \alpha = 0.51 \) and \( \beta = 1.6 \) corresponding to the observed spectral indices at radio/X-ray and optical energies. However, the equipartition magnetic field deduced from equations (2), (3) and (6) is

\[
B_{\text{eq}} \sim 0.67 \left( \frac{\Gamma}{26} \right)^{-1.85} \left( \frac{F_{\nu, \text{syn}}(\nu^*)}{8 \text{ Jy}} \right)^{0.28} \left( \frac{t_{\text{var}}}{1 \text{ d}} \right)^{-0.85} \times \left( \frac{\nu_{\text{min}}}{40} \right)^{-0.006} \left( \frac{\nu}{3 \times 10^{11} \text{Hz}} \right)^{0.15} \text{G}. \quad (25)
\]

Hence, we require a magnetic field much lower than its equipartition value to reproduce the observed X-ray flux through EC scattering of the IR photons. However, if X-ray emission is due to the SSC process, the required magnetic field will be close to its equipartition value.

Based on these arguments, we model the broad-band spectrum of 3C 279 considering synchrotron, SSC and EC processes. The synchrotron emission is dominant at radio/optical energies, whereas SSC is dominant at X-ray energy and EC at VHE gamma-ray energy.

### 4 RESULT AND DISCUSSION

The main parameters governing the observed broad-band spectrum of 3C 279 are the \( B, K, p, q, \gamma_{0}', R', \Gamma, \nu', \text{and} \nu' \). Out of these the indices \( p \) and \( q \) can be constrained using the observed spectral indices at radio and optical energies. If we assume the target photon energy density \( \nu' \) from the dusty torus as a blackbody, then the peak target photon frequency \( \nu' \) can be written in terms of \( \nu' \) as

\[
\nu' = 2.82 \frac{K_B}{c} \left( \frac{4 \sigma}{c} \int \nu' d\nu' \right)^{1/4}. \quad (26)
\]

where \( K_B \) is the Boltzmann constant and \( \sigma \) is the Stefan–Boltzmann constant. The remaining six parameters \( B, K, \gamma_{0}', R', \Gamma, \nu' \) can be calculated using equations (2), (3), (6), (7), (11) and (20). We consider one day as the variability time-scale \( t_{\text{var}} \) (Hartman et al. 1996). The derived parameters are given in Table 1 and the corresponding broad-band spectrum is shown in Fig. 1. We have chosen \( \gamma_{\text{min}} = 40 \) and \( \gamma_{\text{max}} = 1.0 \times 10^3 \) to extend the observed spectrum from radio to very high energies. The approximate expressions for synchrotron, SSC and EC fluxes (discussed in the earlier section and

| Parameter | Symbol | Numerical value |
|-----------|--------|----------------|
| Particle spectral index (low energy) | \( p \) | 2.02 |
| Particle spectral index (high energy) | \( q \) | 4.2 |
| Magnetic field (equipartition) | \( B_{\text{eq}} \) | 0.67 G |
| Particle energy density | \( U_{\nu} \) | \( 1.8 \times 10^{-2} \) erg cm^{-3} |
| Particle spectrum break energy (units of \( mc^2 \)) | \( \gamma_{0}' \) | 832 |
| Emission region size | \( R' \) | \( 4 \times 10^{16} \) cm |
| Bulk Lorentz factor | \( \Gamma \) | 26 |
| IR dust temperature | \( T^* \) | 860 K |
| IR dust photon energy density | \( \nu^* \) | \( 4 \times 10^{-3} \) erg cm^{-3} |
Appendices A and B) are used to derive the parameters, whereas for reproducing the observed flux in Fig. 1 the exact expressions are used and solved numerically. With the given set of parameters if we consider that the number of cold protons is equal to the number of non-thermal electrons, then the energy density due to protons will be \( \sim 1.5 \times 10^{-3} \text{ erg cm}^{-3} \). This is an order less than the electron energy density (Table 1) and hence its exclusion will not affect \( B_{\text{eq}} \) considerably.

From Fig. 1, one can find that the model predicts excessive flux at MeV energies which is nearly an order more than the highest flux detected from 3C 279 by EGRET during its entire mission (Hartman et al. 2001). The flux obtained during 2008 observations by Fermi is also much lower. Hence, it can be argued that this prediction may be unlikely. However, there were no simultaneous observations of the source at MeV–GeV energies during the WEBT campaign and MAGIC detection, and hence such a dramatic flare cannot be ruled out.

The deduced temperature of the dusty torus (\( T = 860 \text{ K} \)) is consistent with the temperature obtained from the inner region of the dusty torus (>800 K) of the nearby Seyfert type 2 AGN NGC 1068 (Jaffe et al. 2004). It is also close to the temperature range (900 – 1300 K) suggested by de Vries et al. (1998) based on near-IR modelling of a gigahertz-peaked spectrum, compact steep spectrum and Fanaroff–Riley type II sources.

The emitted VHE photons can be absorbed by soft target photons through the photon–photon pair production mechanism. The condition on photon energies to be transparent against pair formation is

\[
(1 + \frac{\nu}{\nu_c}) < (mc^2)^2.
\]

If \( \nu_c = 10^{26} \text{ Hz} \), then it can pair produce with target photons with frequency \( \nu^* > 10^{14} \text{ Hz} \). Hence, the emitted VHE photons can pair produce with the BLR photons; however, the IR photons from the dusty torus will be below the threshold. If the emission region is within the BLR, the VHE photons can be absorbed by the BLR photons through pair production (Bai, Liu & Ma 2009; Böttcher et al. 2009). Hence, the detection of 3C 279 at VHE gamma-ray energies demand that the emission region may be ahead of the BLR to avoid the severe \( \gamma\gamma \) absorption. Bai et al. (2009) studied the \( \gamma\gamma \) absorption of VHE gamma-rays from 3C 279 and suggested that the emission region must be located within the BLR. However, the present work [and also Böttcher et al. (2009)] requires the emission region to be far from the BLR region to reproduce the simultaneous broad-band spectrum of 3C 279.

If we consider the dusty torus as an annular ring covering the central source (Pier & Krolik 1992), then the distance of the inner wall of the torus \( (R_{\text{d}}) \) can be estimated as

\[
R_{\text{d}} \approx \frac{1}{\Gamma^2} \sqrt{\frac{L_{\text{acc}}}{4\pi \sigma}} \\
\approx 1.6 \left( \frac{T}{860 \text{ K}} \right)^{-2} \left( \frac{L_{\text{acc}}}{10^{36} \text{ erg s}^{-1}} \right)^{1/2} \text{ pc},
\]

where \( L_{\text{acc}} \) is the accretion disc luminosity. Also, if the distance between BLR clouds and the central source \( (R_{\text{BLR}}) \) of 3C 279 satisfies the size–luminosity relation of Kaspi et al. (2007), then

\[
R_{\text{BLR}} \sim 0.052 \left( \frac{L_{\text{acc}}(1350 \text{ Å})}{10^{36} \text{ erg s}^{-1}} \right)^{0.52} \text{ pc}.
\]

For the considered variability time-scale of 1 d (Hartman et al. 1996), the distance of the emission region from the central source \( (R_{\text{d}}) \) can be approximated as

\[
R_{\text{d}} \sim c t_{\text{var}} \Gamma^2 \approx 0.6 \left( \frac{t_{\text{var}}}{1 \text{ d}} \right) \left( \frac{\Gamma}{24} \right)^2 \text{ pc},
\]

which is \( \approx 10 \) times farther than \( R_{\text{BLR}} \) supporting our inference. Also from equation (28), the emission region lies within the dusty torus, i.e. \( R_{\text{BLR}} < R_{\text{d}} < R_{\text{R}} \).

Böttcher et al. (2009) suggested a multizone leptonic model as a possibility to explain the VHE emission from 3C 279 since the one-zone model requires low magnetic fields and/or a very high Lorentz factor of the jet. However, they arrived to this conclusion by considering the BLR photons as the target photons for the external Compton process instead of IR photons from the dusty torus. Błazejowski et al. (2000) considered a model which is similar to the one described in the present work, but their aim was to project the importance of the Comptonization of IR photons from the torus to reproduce the high-energy spectrum. In the present work, we have used simultaneous observation of 3C 279 at different energies to deduce the physical parameters of the source.

5 CONCLUSION

We reproduce the observed simultaneous broad-band spectrum of 3C 279 using a simple one-zone leptonic model considering synchrotron, SSC and EC processes. From the radio/optical synchrotron spectrum, we show that the VHE emission cannot be attributed to the SSC process, whereas EC scattering of IR photons from the dusty torus can explain the observed VHE emission. Interpreting the X-ray emission as continuation of the EC spectrum requires a magnetic field much lower than its equipartition value. However, an explanation based on the SSC origin of X-ray requires a magnetic field which is comparable to the equipartition value.

The model predicts large flux at MeV–GeV energies. Since the data in this energy range are not available during the considered flare, such a prediction cannot be ruled out. The model parameters describing the source are estimated by considering a magnetic field which is in equipartition with the particle energy density. A deviation from this condition will reflect in the value of the estimated parameters. Also if the jet matter contains considerable amount of energetic protons, then the contribution from these protons should be included in the SSC process. However, in this work, the proton contribution to the total particle energy is considered to be negligible. Also the size of the emission region estimated from equation (3) is only an upper limit and the actual size may be smaller. Moreover, in reality the size of the emission region may be different for different energy bands. These variations in the emission region size will also be reflected in the estimated parameters.

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APPENDIX A: SYNCHROTRON EMISSIVITY

The synchrotron emissivity $\epsilon_{\text{syn}}(v)$ at frequency $v$ due to a relativistic electron distribution $N(\gamma)$ can be written as

$$\epsilon_{\text{syn}}(v) = \frac{1}{4\pi^2} \int_1^\infty P_{\text{syn}}(\gamma', v) N(\gamma') d\gamma'.$$

(A1)

where $P_{\text{syn}}(\gamma', v)$ is the average synchrotron power emitted by an electron with energy $\gamma mc^2$ at frequency $v$. Following Shu (1991), we can express $P_{\text{syn}}(\gamma', v)$ as

$$P_{\text{syn}}(\gamma', v) = \frac{4}{3} \beta^2 \gamma'^2 \sigma_T u_B \phi_\gamma(\gamma'),$$

(A2)

where $\beta = c \nu / \gamma c$ is the velocity of the electron and the function $\phi_\gamma(\gamma)$ satisfies

$$\int_0^\infty \phi_\gamma(\gamma') d\gamma' = 1.$$  

(A3)

If we approximate $\phi_\gamma(\gamma)$ as a delta function,

$$\phi_\gamma(\gamma) \rightarrow \delta(\nu - \gamma v_L),$$

(A4)

then we can perform the integration (A1) and the synchrotron emissivity will be

$$\epsilon_{\text{syn}}(v) \approx \frac{\sigma_T B^2}{48\pi^2} L^{-3/2} N \left( \frac{\nu}{v_L} \right)^{1/2}.$$  

(A5)

APPENDIX B: SSC EMISSIVITY

The SSC emissivity $\epsilon_{\text{ssc}}(v)$ at frequency $v$ due to a relativistic electron distribution $N(\gamma)$ can be written as

$$\epsilon_{\text{ssc}}(v) = \frac{1}{4\pi} \int_1^\infty P_{\text{ssc}}(\gamma', v) N(\gamma') d\gamma',$$

(B1)

where $P_{\text{ssc}}(\gamma', v)$ is the average SSC power emitted by an electron with energy $\gamma mc^2$ at frequency $v$ and can be written as

$$P_{\text{ssc}}(\gamma', v) = \frac{4}{3} \beta^2 \gamma'^2 \sigma_T \int_0^\infty U(\xi) d\xi \psi_\xi(\xi', \gamma'),$$

(B2)

where

$$U_{\text{ps}} = \int_0^\infty U(\xi) d\xi$$

(B3)

is the energy density of the target photons (in this case synchrotron photons) and $\xi$ is the frequency of the target photon. The function $\psi_\xi(\xi', \gamma')$ will satisfy the condition

$$\int_0^\infty \psi_\xi(\xi', \gamma') d\gamma' = 1.$$  

(B4)

Since the frequency $(v)$ of the photon scattered at the Thomson regime is $v \approx \gamma^2 \xi$, we can approximate $\psi_\xi(\xi', \gamma')$ as a delta function,

$$\psi_\xi(\xi', \gamma') \rightarrow \delta(v - \gamma^2 \xi).$$

(B5)

The SSC emissivity will then be

$$\epsilon_{\text{ssc}}(v) \approx \frac{1}{3\pi^2} \sigma_T \int_1^\infty U \left( \frac{v}{\gamma^2} \right) N(\gamma') d\gamma'.$$

(B6)

If we write

$$U(\xi) = \frac{4\pi R}{c} \epsilon_{\text{syn}}(\xi),$$

(B7)
then from equation (A5) we get
\[ \epsilon_{ssc}(\nu) \approx \frac{Rc}{36\pi^2} \sigma_i^2 B^2 v_L^{-3/2} \nu^{1/2} \int_1^\infty \frac{d\gamma}{\gamma} N \left( \frac{1}{\gamma} \sqrt{\frac{\nu}{v_L}} \right) N(\gamma). \] (B8)

For a broken power-law electron distribution (equation 1) we get
\[ \epsilon_{ssc}(\nu) \approx \frac{Rc}{36\pi^2} K^2 \sigma_i^2 B^2 v_L^{-3/2} \nu^{1/2} f(\nu), \] (B9)
where
\[
f(\nu) = \left[ \left( \frac{\nu}{v_L} \right)^{-p/2} \ln \left( \frac{\gamma_1}{\gamma_2} \right) + \frac{\gamma_3^{(q-p)}}{q-p} \left( \frac{\nu}{v_L} \right)^{-q/2} \right]
\times \left( \gamma_1^{(q-p)} - \gamma_2^{(q-p)} \right) \Theta \left( \frac{\nu}{v_L} - \gamma_1 \right)
\]
\[
+ \left[ \gamma_2^{2(q-p)} \left( \frac{\nu}{v_L} \right)^{-q/2} \ln \left( \frac{\gamma_4}{\gamma_5} \right) + \frac{\gamma_6^{(q-p)}}{q-p} \left( \frac{\nu}{v_L} \right)^{-q/2} \right]
\times \left( \gamma_2^{(p-q)} - \gamma_3^{(p-q)} \right) \Theta \left( \gamma_4 - \nu \right). \]
(B10)

Here \( \Theta \) is the Heaviside function and
\[
\begin{align*}
\gamma_1 &= \text{MAX} \left( \gamma_{\min}, \frac{1}{\gamma_b} \sqrt{\frac{\nu}{v_L}} \right), \quad \text{(B11)} \\
\gamma_2 &= \text{MIN} \left( \gamma_b, \frac{1}{\gamma_{\min}} \sqrt{\frac{\nu}{v_L}} \right), \quad \text{(B12)} \\
\gamma_3 &= \text{MAX} \left( \gamma_b, \frac{1}{\gamma_{\max}} \sqrt{\frac{\nu}{v_L}} \right), \quad \text{(B13)} \\
\gamma_4 &= \text{MIN} \left( \gamma_{\max}, \frac{1}{\gamma_b} \sqrt{\frac{\nu}{v_L}} \right). \quad \text{(B14)}
\end{align*}
\]