Non-variable TeV emission from the extended jet of a blazar in the stochastic acceleration scenario: the case of the hard TeV emission of 1ES 1101–232

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ABSTRACT
The detections of X-ray emission from the kiloparsec-scale jets of blazars and radio galaxies could imply the existence of high-energy electrons in these extended jets, and these electrons could produce high-energy emission through the inverse Compton (IC) process. In this paper, we study the non-variable hard TeV emission from a blazar. The multiband emission consists of two components: (i) the traditional synchrotron self-Compton (SSC) emission from the inner jet; (ii) the emission produced via SSC and IC scattering of cosmic microwave background (CMB) photons (IC/CMB) and extragalactic background light (EBL) photons by relativistic electrons in the extended jet under the stochastic acceleration scenario. Such a model is applied to 1ES 1101–232. The results indicate the following. (i) The non-variable hard TeV emission of 1ES 1101–232, which is dominated by IC/CMB emission from the extended jet, can be reproduced well by using three characteristic values of the Doppler factor ($\delta_D = 5, 10$ and $15$) for the TeV-emitting region in the extended jet. (ii) In the cases of $\delta_D = 15$ and 10, the physical parameters can achieve equipartition (or quasi-equipartition) between the relativistic electrons and the magnetic field. In contrast, the physical parameters largely deviate from equipartition for the case of $\delta_D = 5$. Therefore, we conclude that the TeV emission region of 1ES 1101–232 in the extended jet should be moderately or highly beamed.

Key words: radiation mechanisms: non-thermal – galaxies: active – BL Lacertae objects: individual: 1ES 1101–232 – gamma-rays: general.

1 INTRODUCTION
Blazars are the most extreme class of active galactic nuclei (AGNs). Their spectral energy distributions (SEDs) are characterized by two distinct bumps. The first bump, which is located at the low-energy band, is dominated by the synchrotron emission of relativistic electrons in a relativistic jet. The second bump, which is located at the high-energy band, could be produced by inverse Compton (IC) scattering (e.g. Böttcher 2007). Various soft photon sources seed the synchrotron self-Compton (SSC) process (e.g. Rees 1967; Maraschi, Ghisellini & Celotti 1992) and the external Compton (EC) process (e.g. Dermer & Schlickeiser 1993; Sikora, Begelman & Rees 1994) in the jet to produce $\gamma$-rays. Hadronic models have also been proposed to explain the multiband emissions of blazars (e.g. Mannheim 1993; Mücke et al. 2003).

More than 40 blazars have been detected in the TeV band and most of these are high-frequency peaked BL Lacertae objects (HBLs). The GeV–TeV photons from blazars would be absorbed by interaction with extragalactic background light (EBL) photons, through the pair-production process (e.g. Stecker, de Jager & Salamon 1992). Therefore, the observed high-energy emission from a TeV blazar must be less luminous and its spectrum must be steeper compared with its intrinsic emission. A large amount of observational evidence supports the fact that the TeV emission of HBLs can be explained by the SSC radiation inside their jets. However, recent observations of TeV emission from some HBLs have challenged the classic SSC scenario. Indeed, the intrinsic TeV spectra of some relatively distant sources – for example, 1ES 0229+200 ($z = 0.14$; Aharonian et al. 2007a), 1ES 1101–232 ($z = 0.186$; Aharonian et al. 2006) and 1ES 0347–121 ($z = 0.188$; Aharonian et al. 2007b) – are very hard (with the intrinsic TeV spectral index $\Gamma_{\text{int}} \sim 1.5$), even considering the low-level EBL models (e.g. Franceschini, Rodighiero & Vaccari 2008; Finke, Razzauque & Dermer 2010). The standard shock acceleration theories predict the particle distribution index $p \geq 2$, where $n(\gamma) = \gamma^{-p}$. This would correspond to a limiting intrinsic photon spectral index $\Gamma_{\text{int}} \geq 1.5$. Moreover, because the suppression of the cross-section as a result of the Klein–Nishina (KN) effect becomes important in the TeV emission from HBLs, steeper intrinsic photon spectra would be expected.

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Many possible solutions have been proposed to overcome this problem of hard TeV emission. Katarzyński et al. (2006a) have suggested that the hard TeV emission of IES 1101–232 can be explained in the SSC scenario by assuming a narrow distribution of high-energy electrons with a large value of minimum energy cut-off ($\sim 10^8$). As shown by Tavecchio et al. (2009), this solution might be supported by the simultaneous ultraviolet (UV) and X-ray observations of IES 0229+200, performed by the Swift satellite. However, this scenario would require the emission process to be very inefficient and the acceleration process to be very efficient. The formation of such hard TeV emission could also be achieved in an internal absorption scenario (Aharonian, Khangulyan & Costamante 2008; Zacharopoulou et al. 2011). Very recently, Lefa, Rieger & Aharonian (2011a) have suggested that the consideration of either adiabatic losses or relativistic Maxwell-like distributions formed by a stochastic acceleration is an alternative option to create hard TeV spectra. Lefa, Aharonian & Rieger (2011b) have shown that the relative hard $\gamma$-ray spectrum of Mrk 501 could be formed in a multizone model in the stochastic acceleration scenario. The secondary $\gamma$-rays produced relatively close to the Earth by the interactions of cosmic ray protons with background photons can also explain the hard TeV emission of blazars (e.g. Essey et al. 2011; Murase et al. 2012).

Previously, authors have usually considered the emissions from the inner jets (subparsec scale) of blazars. As an alternative, Böttcher, Dermer & Finke (2008) have suggested that the slowly variable, hard TeV emission of IES 1101–232 might be created via Compton upscattering of cosmic microwave background (CMB) photons by shock-accelerated electrons in an extended jet (kilo-parsec scale). X-ray emissions from the extended jets of blazars have been detected (e.g. Tavecchio et al. 2007; Sambruna et al. 2008; Massaro, Harris & Cheung 2011). This evidence implies the presence of high-energy electrons in their extended jets. In such an extended jet, the CMB photons would be dominant soft photons for the IC process (e.g. Tavecchio et al. 2000). The emission of Compton upscattering of the EBL photons off relativistic electrons might also be important at the TeV band (Georganopoulos et al. 2008), because of the Doppler effect. Moreover, recent studies have indicated that electrons in the large-scale jets of AGNs might be accelerated to high energies by stochastic acceleration (e.g. Fan et al. 2008; O’Sullivan, Reville & Taylor 2009). Possible TeV emissions from the extended jets of some radio galaxies have been explored (e.g. Hardcastle & Croston 2011; Zhang et al. 2009, 2010). In the AGN unification scheme (Urry & Padovani 1995), it is natural and worthwhile to wonder whether the type of non-variable TeV emissions of some blazars can be produced, at least in part, in their extended jets.

In this paper, we study possible TeV emission from the extended jet of a blazar. We assume that multiband emission from a non-variable TeV blazar includes two components, one from the inner jet and the other from the extended jet. In this model, the emission from the inner jet is produced in a conventional SSC model, and the emission from the extended jet is produced in a self-consistent SSC+CMB/EBL model under the stochastic acceleration scenario. We apply the model to explain the non-variable hard TeV emission of IES 1101–232. The cosmological parameters ($H_0$, $\Omega_m$, $\Omega_{\Lambda}$) = (70 km s$^{-1}$ Mpc$^{-1}$, 0.3, 0.7) are used throughout this paper.

### 2 THE MODEL

As mentioned above, we assume that the emission from a non-variable TeV blazar is produced at both the inner and extended jets. In this model, non-thermal photons are produced by both the synchrotron radiation and IC scattering of relativistic electrons in a spherical blob, which is moving relativistically at a small angle to our line of sight, and the observed radiation is strongly boosted by a relativistic Doppler factor $\delta_D$. We give the specific descriptions of this model below.

#### 2.1 Conventional SSC model in the inner jet

We use the conventional SSC model to produce the emission from the inner jet. Here, we assume a broken power-law electron energy distribution and we use the relativistic electron distribution given by Dermer et al. (2009):

\[
N'(\gamma') = K'_{\epsilon} \frac{1}{\gamma'} \exp \left(-\gamma'/\gamma'_0\right) \times H \left(\gamma''_0 - \gamma'\right) + \left[\left(\gamma''_0 - \gamma''_1\right) \frac{\gamma''_{1-\gamma''_1}}{\gamma''_0} \right] \frac{\gamma''_{1-\gamma''_1}}{\gamma''_0} \exp \left(p_1 \gamma''_1 - \gamma''_{1-\gamma''_1}\right) \right],
\]

(1)

Here, $K'_{\epsilon}$ is the normalization factor, in units of cm$^{-3}$, and $H(\gamma''_0; \gamma''_1, \gamma''_2)$ is the Heaviside function, where $H(\gamma''_0; \gamma''_1, \gamma''_2) = 1$ for $\gamma''_1 < \gamma''_0 < \gamma''_2$ and $H(\gamma''_0; \gamma''_1, \gamma''_2) = 0$ everywhere else, and $H(\gamma''_0; \gamma''_1, \gamma''_2) = 1$ for $\gamma''_0 > \gamma''_1$. The minimum and maximum energies of the electrons in the blob are $\gamma'_0$ and $\gamma'_1$, respectively. The spectrum is smoothly connected with indices $p_1$ and $p_2$ below and above the electron’s break energy $\gamma'_0$. Note that here and throughout the paper, unprimed quantities refer to the distant observer’s frame on the Earth and primed quantities refer to the comoving frame.

Then, the synchrotron flux is calculated as (Finke, Dermer & Böttcher 2008)

\[
\nu F^{\text{syc}}_\nu = \frac{\sqrt{3}\delta_B^4 e^3 B^2}{4\pi h c^4} \int_0^\infty d\nu' N'_{\nu'}(\gamma') \left(4\pi R_b^2 / 3\right) R(x),
\]

(2)

where $e$ is the electron charge, $B$ is the magnetic field strength, $R_b$ is the blob’s radius, $h$ is the Planck constant and $d_4$ is the distance to the source with a redshift $z$. Here, $m_e c^2 e^+ = h\nu(1 + z)/\delta_D$ is the energy of the synchrotron photons in the comoving frame, where $m_e$ is the rest mass of electrons and $c$ is the speed of light. Here, we use an approximation for $R(x)$ given by Finke et al. (2008). The synchrotron spectral energy density is

\[
\nu F^{\text{syc}}_\nu = \frac{R_b^2}{c} \frac{\sqrt{3} e^3 B^2}{h} \int_0^\infty d\nu' N'_{\nu'}(\gamma') R(x),
\]

(3)

The SSC flux $\nu F_\nu$ is given by Finke et al. (2008) as

\[
\nu F^{\text{SSC}}_\nu = \frac{3}{4} \frac{\sigma_T e^2}{4\pi} \int_0^\infty d\nu' \frac{\nu F^{\text{syc}}_\nu}{e^2} \times \frac{d\nu'}{\nu'} \int_{\nu'_\min}^{\nu'_\max} d\nu' N'_{\nu'}(4\pi R_b^2 / 3) F_{C}(q', \Gamma'_e),
\]

(4)

where $\sigma_T$ is the Thomson cross-section, $m_e c^2 e^+ = h\nu(1 + z)/\delta_D$ is the energy of IC scattered photons in the comoving frame,

\[
F_{C}(q', \Gamma'_e) = 2q' \ln q' + (1 + 2q') (1 - q') + \frac{q'^2 \Gamma'_e}{2(1 + q' \Gamma'_e)} (1 - q'),
\]

\[
q' = \frac{\nu'/\Gamma'_e}{\Gamma'_e(1 - \nu'/\nu')},
\]

\[
\Gamma'_e = 4\epsilon' \nu' \quad \text{and} \quad 1/(4\epsilon' \nu') \leq q' \leq 1.
\]
2.2 Self-consistent SSC+IC/CMB/EBL model in the extended jet under the stochastic acceleration scenario

The self-consistent SSC+IC/CMB/EBL model, including an acceleration process in the stochastic acceleration scenario, is used to create the emission from the extended jet. A physical self-consistent description of stochastic acceleration in a time evolution scenario can be achieved through a kinetic equation. This kinetic equation is given as (Katarzyński et al. 2006b; see also Weidinger, Rüger & Spanier 2010; Tramacere, Massaro & Taylor 2011)

\[
\frac{\partial N(y', t)}{\partial t} = \frac{\partial}{\partial y'} \left\{ \left[C(y', t) - A(y', t)\right] N(y', t) \right\}
+ \frac{\partial}{\partial y'} \left[ D(y', t) \frac{\partial N(y', t)}{\partial y'} \right] - E(y', t) + Q(y', t).
\]

(5)

Here, \(D(y', t)\) is the momentum diffusion coefficient and \(A(y', t) = (2/\gamma')D(y', t)\) is the average energy change term that results from the momentum-diffusion process. In this paper, we assume that the acceleration time-scale \(\tau_{\text{acc}}\) and escape time-scale \(\tau_{\text{esc}}\) are both independent of electron energy, which is the case of the hard sphere approximation. Hence, \(D(y') = (1/2\gamma)\gamma'^{-2}\), \(A(y') = \gamma'/\tau_{\text{acc}}\) and the escape term \(E(y') = N(y', t)\tau_{\text{esc}}\). Here, \(Q(y', t)\) is the injection term and \(C(y', t)\) is the total cooling rate. In addition to the synchrotron cooling rate \((d\gamma'/d\gamma)_{\text{syn}}\) and the SSC cooling rate \((d\gamma'/d\gamma)_{\text{SSC}}\), we consider the IC/CMB cooling rate \((d\gamma'/d\gamma)_{\text{IC/CMB}}\) and the IC/EBL cooling rate \((d\gamma'/d\gamma)_{\text{IC/EBL}}\). Therefore,

\[
C(y', t) = \left( \frac{d\gamma'}{d\gamma} \right)_{\text{syn}} + \left( \frac{d\gamma'}{d\gamma} \right)_{\text{SSC}} + \left( \frac{d\gamma'}{d\gamma} \right)_{\text{IC/CMB}} + \left( \frac{d\gamma'}{d\gamma} \right)_{\text{IC/EBL}}.
\]

For synchrotron cooling,

\[
\left( \frac{d\gamma'}{d\gamma} \right)_{\text{syn}} = \frac{4\epsilon}{3m_e c^2} U_{\text{B}} y^2,
\]

where \(U_{\text{B}} = B^2/8\pi\) is the magnetic field energy density. The SSC cooling rate using the full KN cross-section (e.g. Jones 1968; Böttcher, Mause & Schlickeiser 1997; Finke et al. 2008) is

\[
\left( \frac{d\gamma'}{d\gamma} \right)_{\text{SSC}} = \frac{3\epsilon}{8m_e c} \int_0^{\infty} \frac{\epsilon' \sigma_{\text{syn}}(\epsilon')}{\epsilon'^2} G(\gamma' \epsilon') \, d\epsilon'.
\]

(6)

Here,

\[
G(E) = \frac{8}{3} E \left( 1 + 4E^2 \right) \left( 1 + \frac{4}{1 + 4E^2} \right) - \frac{2}{3} \left( \frac{1 + 3}{4} + \frac{1}{2E^2} \right) \ln(1 + 4E) - \frac{1}{2E} \ln(4E) + \frac{5}{2} \ln \left( \frac{1 + 4E}{2} \right)
+ \frac{1}{2} \sum_{n=1}^{\infty} \frac{(1 + 4E)^n - \pi^2}{n^2} - \frac{\pi^2}{6} E^{-2} - 2,
\]

and \(\epsilon_{\text{syn}}(\epsilon')\) is given by equation (3). We calculate the IC/CMB and IC/EBL cooling rates using the method given by Moderski et al. (2005), which fully takes into account the KN effects,

\[
\left( \frac{d\gamma'}{d\gamma} \right)_{\text{IC/CMB/EBL}} = \frac{4\epsilon}{3m_e c^2} y' y^2 F_{\text{KN}}.
\]

(7)

Here, \(F_{\text{KN}} = \int_{\gamma_{\text{CM}}}^{\gamma_{\text{CM}}} f_{\text{KN}}(4\gamma' \epsilon' u_{\text{CM/EBL}}(\epsilon')) d\epsilon'\), and \(f_{\text{KN}}(x) \simeq (9/2x^2)(\ln(x) - 11/6)\) for \(x \gg 1\), where \(f_{\text{KN}}(x)\) can be approximated by \(f_{\text{KN}}(x) \simeq 1/(1 + x)^{1.5}\) for \(x \lesssim 10^4\). For the case of the CMB radiation in the stationary frame of the host galaxy,

\[
u_{\text{CM/EBL}}(\epsilon) = \frac{8\pi m_e c^2}{h^3} \frac{\epsilon^3}{\exp(\epsilon/\Theta) - 1},
\]

where \(\Theta = k_B T_{\text{BLR}} c^2\) is the dimensionless temperature of the blackbody radiation field, \(T = 2.72(1 + z)\) K and \(k_B\) is the Boltzmann constant. We use the spectral EBL energy density expected in Finke et al. (2010). The spectral energy densities in the comoving frame transform as \(\nu'(\epsilon') = \delta_{\text{EBL}}(\epsilon'/\Theta)\) (e.g. Ghisellini & Tavecchio 2009).

To obtain the self-consistent relativistic electron energy distribution, we must solve equation (5) numerically. In the numerical calculations, we adopt the numerical method given by Park & Petrosian (1996), which was first proposed by Chang & Copper (1970). The method is a finite difference scheme, which uses the centred difference of the diffusive term, and a weighted difference for the advective term. We have carefully tested our code by running it with parameters identical to those used for fig. 4 of Katarzyński et al. (2006b), only considering the synchrotron and SSC radiative cooling. We find good agreement with their results. Fig. 1 shows the electron spectra from fig. 4 of Katarzyński et al. (2006b) reproduced using our code.

After obtaining the relativistic electron energy distribution, we can calculate the synchrotron–SSC flux and the IC/CMB/EBL flux from the extended jet by using equations (2) and (4) with the corresponding electron spectrum and energy densities of the soft photon field.

The high-energy emission from both the inner and extended jets would be modified by a factor of \(\exp(- \tau)\) because of the absorption of EBL. In this paper, we use the optical depth \(\tau\) expected by Finke et al. (2010). This EBL model is a low-level model, which is consistent with the widely used (e.g. Franceschini et al. 2008) and newly proposed (e.g. Domínguez et al. 2011) models.

3 APPLICATION TO 1ES 1101–232

1ES 1101–232 resides in an elliptical host galaxy (e.g. Remillard et al. 1989). An extended jet structure at a few kiloparsec distance from the core is revealed by the radio observations (Laurent-Muehleisen et al. 1993). The TeV observations of 1ES 1101–232 were performed by the High-Energy Stereoscopic System (HESS) Cherenkov telescopes in 2004 April and June, and in 2005 March. Following the detection of a weak signal in the 2004 HESS observations, simultaneous X-ray measurements with the RXTE and optical measurements with the Robotic Optical Transient Search Experiment (ROTSE) 3c robotic telescope were carried out in 2005

![Figure 1. The electron spectra from fig. 4 of Katarzyński et al. (2006b) reproduced using our code.](https://example.com/figure1.png)
March (Aharonian et al. 2007c). No TeV variability was found in these observations, and moderate flux changes were observed with the RXTE in 2005 March (Aharonian et al. 2007c). No very significant signal from 1ES 1101–232 was detected by the Large Area Telescope (LAT) onboard Fermi in its first year of scientific operation (Abdo et al. 2010a), and only the flux upper limits derived from the first-year Fermi-LAT observations are available (e.g. Neronov & Vovk 2010; Costamante 2011). The two-year scientific operation of Fermi-LAT has reported a significant detection of 1ES 1101–232 at a significance 5.2$\sigma$ with the photon spectral index $\Gamma = 1.80 \pm 0.31$ (Ackermann et al. 2011). More significant signals ($\sigma \sim 10$) from 1ES 1101–232 have been detected in the Fermi-LAT 3.5-yr observations (Finke, Georgopoulous & Reyes 2012). We use the Fermi-LAT 3.5-yr average spectrum. Because the detections made by HESS in 2004 are not significant, in this paper we select the simultaneous multiband data derived in the observations in 2005 March.

A variability has been detected at the optical and X-ray frequencies of 1ES 1101–232 (e.g. Remillard et al. 1989; Romero, Cellone & Combi 1999; Wolter et al. 2000). Moreover, the IC/CMB process has a radiative cooling time-scale $\sim 10^4$ yr (Böttcher et al. 2008), and such a long cooling time-scale indicates that the IC/CMB emission, as well as the synchrotron emission associated with the same high-energy electrons and emission region, will be slowly variable. In addition, the very large size of the emission region in the extended jet (e.g. Tavecchio et al. 2007; Fan et al. 2008) also indicates that emission from such a region should be slowly variable. Therefore, we argue that the moderately variable optical–X-ray radiation of 1ES 1101–232 should be dominated by the emissions originating in a compact region in the inner jet.

As discussed above, we use the conventional SSC model in the inner jet to produce the optical–X-ray emission. The self-consistent SSC+IC/CMB/EBL model is used to create the TeV emission from the extended jet. In the extended jet, we assume that electrons with energy $\gamma_\text{inj} \approx 27$ are continuously injected into a blob with a constant injection rate $Q'$. The minimum and maximum energies of electrons in this blob are set as $\gamma_\text{min} = 1.0$ and $\gamma_\text{max} = 10^3$.

The Doppler effect is crucial for the IC/CMB/EBL emission because it can affect the CMB energy density and the CMB photon energy in the comoving frame, and inversely it affects the relativistic electron energy density required to produce the TeV emission. Unfortunately, the Doppler factor is poorly constrained. It is possible that the jets of blazars remain highly relativistic at kiloparsec scales (e.g. Atoyan & Dermer 2004; Jorstad & Marscher 2004). However, recent very long baseline interferometry (VLBI) observations indicate that the bulk Lorentz factors in the parsec-scale radio jets of TeV HBLs are fairly low, $\Gamma < 5$ (e.g. Piner, Pant & Edwards 2008, 2010). Because of the importance of the Doppler effect, we assume three values of Doppler factor for the TeV emission region in the extended jet: $\delta_0 = 15$, 10 and 5. These correspond to the highly beamed, moderately beamed and mildly beamed cases, respectively, to reproduce the TeV emission of 1ES 1101–232. In the following, we show the results for reproducing the SED.

(i) Highly beamed extended jet with $\delta_0 = 15$. These results are shown in Fig. 2. It can be seen that when $t > 9 t_\text{esc}$, the electron spectrum produced by the stochastic acceleration tends to be steady. This distribution in the steady state develops a rising low-energy power-law tail (left side of $\gamma'_\text{inj}$ in the upper panel of Fig. 2) with the theoretical spectral index $n \approx -2 \pm t_\text{esc}/2t_\text{esc}$ (the acceleration theory predicts $n \approx -2.43$, and our numerical calculations give $n \approx -2.49$). However, at high energies, it presents a power-law spectrum with an exponential cut-off (right side of $\gamma'_\text{inj}$ in the upper panel of Fig. 2). The spectral index of the power-law distribution formed in the stochastic acceleration scenario at $\gamma' > \gamma_\text{inj}$ is $n \approx 1 + (t_\text{esc}/2t_\text{esc})$ (the acceleration theory predicts $n \approx 1.43$, and our numerical calculations give $n \approx 1.49$). This differs from the spectral index $n \approx 1 + (t_\text{esc}/H_\text{esc})$, which is obtained from the basic shock acceleration (e.g. Kirk, Rieger & Mastichiadis 1998; Katarzyński et al. 2006b). The cut-off energy can be obtained when the cooling time-scale $t_\text{cool}$ satisfies the condition $t_\text{cool}(\gamma'_\text{inj}) = t_\text{esc}$. We adopt this steady-state electron spectrum to produce the TeV emission from the extended jet. As shown in the lower panel of Fig. 2, a good representation of the SED can be achieved. The synchrotron emission from the inner jet contributes to the optical–X-ray emission of 1ES 1101–232. At the GeV band, SSC emission from the inner jet is dominant. The parameters we have used are appropriate for the emission region in the inner jet with the ratio between the relativistic electrons energy density and the magnetic field energy density, $U'_e/U'_B \approx 0.4$. The parameters are listed in Tables 1 and 2. The IC/CMB emission from the extended jet dominates the TeV emission, while the IC/EBL emission and the SSC emission from the extended jet are negligible in this case. Our results indicate that the intrinsic TeV flux peak is located at $\sim$4 TeV, and the intrinsic TeV spectral index is $\Gamma_{\text{jet}} \sim 1.5$. These values are consistent with those inferred by Aharonian et al. (2007c). As required, the injected TeV HBLs are fairly low, cate that the bulk Lorentz factors in the parsec-scale radio jets of (e.g. Atoyan & Dermer 2004; Jorstad & Marscher 2004). However, that the jets of blazars remain highly relativistic at kiloparsec scales Fortunately, the Doppler factor is poorly constrained. It is possible that the moderately variable optical–X-ray radiation of 1ES 1101–232 should be dominated by the emissions originating in a compact region in the inner jet. As discussed above, we use the conventional SSC model in the inner jet to produce the optical–X-ray emission. The self-consistent SSC+IC/CMB/EBL model is used to create the TeV emission from the extended jet. In the extended jet, we assume that electrons with energy $\gamma_\text{inj} \approx 27$ are continuously injected into a blob with a constant injection rate $Q'$. The minimum and maximum energies of electrons in this blob are set as $\gamma_\text{min} = 1.0$ and $\gamma_\text{max} = 10^3$. The Doppler effect is crucial for the IC/CMB/EBL emission because it can affect the CMB energy density and the CMB photon energy in the comoving frame, and inversely it affects the relativistic electron energy density required to produce the TeV emission. Unfortunately, the Doppler factor is poorly constrained. It is possible that the jets of blazars remain highly relativistic at kiloparsec scales (e.g. Atoyan & Dermer 2004; Jorstad & Marscher 2004). However, recent very long baseline interferometry (VLBI) observations indicate that the bulk Lorentz factors in the parsec-scale radio jets of TeV HBLs are fairly low, $\Gamma < 5$ (e.g. Piner, Pant & Edwards 2008, 2010). Because of the importance of the Doppler effect, we assume three values of Doppler factor for the TeV emission region in the extended jet: $\delta_0 = 15$, 10 and 5. These correspond to the highly beamed, moderately beamed and mildly beamed cases, respectively, to reproduce the TeV emission of 1ES 1101–232. In the following, we show the results for reproducing the SED.

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Table 1. The modelling parameters for the inner jet.

| $B'$ (G) | $\gamma'_\text{min}$ | $\gamma'_\text{max}$ | $\gamma'_b$ | $\delta_D$ | $K'_\text{e}$ (cm$^{-3}$) | $p_1$ | $p_2$ | $R'_\text{e}$ (cm) |
|----------|---------------------|---------------------|-------------|------------|-------------------|-------|-------|----------------|
| Inner jet | 0.1 | 1.0 | $6.0 \times 10^5$ | $2.0 \times 10^5$ | 24.7 | 19.8 | 2.0 | 4.0 | $7.5 \times 10^{10}$ |

Table 2. The modelling parameters for the extended jet.

| $B'$ (µG) | $Q'$ (cm$^{-3}$ s$^{-1}$) | $R'_\text{e}$ (cm) | $t_{\text{esc}}$ (s) | $t_{\text{esc}}/t_{\text{inj}}$ | $\delta_D$ | $U'_\text{e}/U'_\text{b}$ |
|-----------|--------------------------|-------------------|---------------------|-------------------------|------------|------------------|
| Extended jet | | | | | | |
| Highly beamed | 23.0 | $8.0 \times 10^{-20}$ | $5.0 \times 10^{20}$ | $R'_\text{e}/c$ | 0.86 | 15 | 1.0 |
| Moderately beamed | 58.5 | $5.0 \times 10^{-19}$ | $5.0 \times 10^{20}$ | $R'_\text{e}/c$ | 0.86 | 10 | 1.0 |
| Mildly beamed | 29.3 | $1.0 \times 10^{-17}$ | $5.0 \times 10^{20}$ | $R'_\text{e}/c$ | 0.78 | 5 | 112.3 |

Table 3. The radiative ($P_\text{r}$), Poynting flux ($P_\text{b}$), kinetic ($P_\text{e}$ and $P_\text{p}$) and injection ($L_{\text{inj}}$) powers for the inner and extended jets.

| Inner jet | Extended jet | | | | | |
|-----------|-------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| $P_\text{r}$ (erg s$^{-1}$) | 4.1 $\times 10^{43}$ | 1.3 $\times 10^{44}$ | 5.4 $\times 10^{43}$ | 9.2 $\times 10^{45}$ | $-$ |
| $P_\text{b}$ (erg s$^{-1}$) | 1.3 $\times 10^{44}$ | 1.1 $\times 10^{44}$ | 1.1 $\times 10^{44}$ | 1.5 $\times 10^{43}$ | 5.2 $\times 10^{40}$ |
| $P_\text{e}$ (erg s$^{-1}$) | 3.0 $\times 10^{44}$ | 3.2 $\times 10^{44}$ | 3.2 $\times 10^{44}$ | 4.1 $\times 10^{43}$ | 1.4 $\times 10^{41}$ |
| $P_\text{p}$ (erg s$^{-1}$) | 2.0 $\times 10^{43}$ | 2.0 $\times 10^{43}$ | 2.0 $\times 10^{44}$ | 2.0 $\times 10^{44}$ | 7.2 $\times 10^{41}$ |
| $L_{\text{inj}}$ (erg s$^{-1}$) | | | | | | |

\[ L_{\text{inj}} = \frac{4}{3} \pi R_\text{e}^3 \delta_D \frac{B'}{4} Q' \gamma_{\text{inj}} \approx 5.2 \times 10^{40} \text{ erg s}^{-1} \]

(Weidinger 2011) in the stationary frame of the host galaxy for the extended jet (see Table 3) exceeds the observed radio power of the extended radio structure at 1.5 GHz, $L_{\text{ext}}^{1.5} \approx 3.8 \times 10^{40}$ erg s$^{-1}$ (Laurent-Muehleisen et al. 1993). Because of the highly relativistic extended jet, the required energy density of the relativistic electrons is small, $U'_\text{e} \approx 2.1 \times 10^{-11}$ erg cm$^{-3}$. The parameters we have adopted for the extended jet can achieve the equipartition condition between the relativistic electrons and the magnetic field ($U'_\text{e}/U'_\text{b} \approx 1.0$), and the synchrotron emission from the extended jet is about one order of magnitude below the emission from the inner jet.

(ii) Moderately beamed extended jet with $\delta_D = 10$. These results are presented in Fig. 3. In this case, we only present the electron spectrum in the steady state, which is used to reproduce the TeV emission from the extended jet, because the evolution of this electron spectrum is the same as in the former case. The emissions from the inner jet are the same as those in the former case, and TeV emission is also dominated by IC/CMB emission. In this case, the required energy density of relativistic electrons becomes larger, $U'_\text{e} \approx 1.4 \times 10^{-10}$ erg cm$^{-3}$. In order to achieve the equipartition with $U'_\text{e}/U'_\text{b} \approx 1.0$, a larger magnetic field strength ($U'_\text{b} \approx 2U'_{\text{CMB}}$) is needed, which causes significant synchrotron emission from the extended jet. If a magnetic field in quasi-equipartition with the relativistic electrons with $U'_\text{e}/U'_\text{b} \sim 2.0$ is used, the contribution of synchrotron emission from the extended jet will be slight compared to the optical–X-ray emission of IES 1101–232.

(iii) Mildly beamed extended jet with $\delta_D = 5$. We show these results in Fig. 4. The emissions from the inner jet are still unchanged. In this case, in order to reproduce the TeV emission well, a high-energy density of relativistic electrons in the extended jet is needed, $U'_\text{e} \approx 3.8 \times 10^{-9}$ erg cm$^{-3}$. Even if a large magnetic field strength is used ($U'_\text{b} \sim 2U'_{\text{CMB}}$), the parameters with $U'_\text{e}/U'_\text{b} \approx 112.3$ still largely deviate from the equipartition.

\[ P_i = \pi R_\text{b}^2 U'_\text{e}/c, \]

where $U'_i$ (i = r, e, B, p) are the energy densities associated with the radiation $U'_r$, the emitting electrons $U'_e$, the magnetic field $U'_B$ and protons $U'_p$ in the comoving frame. We calculate $U'_p$ by assuming one
proton per emitting electron, then \(U'_p = U'_e(m_p/m_e)/\langle \gamma' \rangle \) (Celotti & Ghisellini 2008), where \(\langle \gamma' \rangle\) is the average energy of relativistic electrons. Here, we take the bulk Lorentz factor \(\Gamma = \delta_0\). Using \(U'_e = L'/4\pi R_s^2 c\), the power carried in the form of the produced radiation can be rewritten as (Celotti & Ghisellini 2008)

\[
P = L'\Gamma^2 \approx L' \frac{\Gamma^2}{\delta_0^2},
\]

where \(L\) is the total non-thermal luminosity.

Our predicted powers are listed in Table 3. For the inner jet, we find that \(P_r \sim P_e \leq P_b\). This follows from the fact that the synchrotron luminosity from the inner jet is larger than the \(\gamma\)-ray one. For extended jets with \(\delta_0 = 10\) and \(15\), we find that \(P_r \sim P_e \sim P_b\). Because \(P_r \sim P_e\), relativistic electrons cannot be the primary energy carriers in the jet (Celotti & Ghisellini 2008). With the assumption of one proton per emitting electron, our results indicate that a substantial fraction of the total jet power in the inner jet is carried by protons. However, it can be seen that in the extended jet, the jet power in the protons is far smaller than in the emitting electrons, with \(P_p/P_e \sim 0.1\). This contradicts the scenario that a sizeable fraction of jet power is carried out to large distances by the proton content of the jet. Moreover, the Poynting flux in the inner jet is comparable with that in the extended jets for \(\delta_0 = 10\) and \(15\). Therefore, as well as the Poynting flux, relativistic leptons also cannot be the primary energy carriers. It is likely that, for 1ES 1101–232, the cold electron positron pairs are the primary energy carriers in the jet (e.g. Celotti & Ghisellini 2008).

As mentioned in Section 1, Böttcher et al. (2008) have modelled the TeV emission from 1ES 1101–232 in the framework of Compton upscattering of CMB photons by shock-accelerated electrons in an extended jet with \(\delta_0 = 15\). It is worth comparing their results with ours. For the extended jet with \(\delta_0 = 15\), the injected power in our model is \(L_{\gamma} = 5.2 \times 10^{40}\) erg s\(^{-1}\) (see Table 3), which is about one-third of that given by Böttcher et al. (2008). The electron distribution index used by Böttcher et al. (2008) is \(n = 1.5\), which is almost the same as the one we have obtained \((n \approx 1.49)\). However, in the framework of shock acceleration, such a small electron distribution index can only result from the extreme condition (Stecker, Baring & Summerlin 2007). However, in the stochastic acceleration model, such a small electron distribution index can be naturally obtained by assuming \(t_{\text{esc}} \sim t_{\text{rec}}\). In order to achieve the equipartition, a larger value \(\sim 23 \mu\text{G}\) and \(U'_b \approx 0.1U'_\text{CMB}\), where \(U'_\text{CMB} = 4.02 \times 10^{-13}(1 + z^4\delta_0^2)\) erg cm\(^{-3}\) of magnetic field strength is required in our model compared to that \((\sim 10 \mu\text{G})\) used by Böttcher et al. (2008), which causes larger synchrotron emission from the extended jet than that derived by Böttcher et al. (2008). For the inner jet, we have assumed that a broken power-law electron distribution creates the non-thermal emission. It can be found that the values of \(\Gamma, R_s, \delta_0\) and \(\gamma_{\text{max}}\) used in our model are very close to the values used by Böttcher et al. (2008). However, the value of \(\gamma_{\text{min}}\) can be as low as one in our inner jet model \((\gamma_{\text{min}} \approx 10^2)\) in Böttcher et al. (2008).

4 DISCUSSION AND CONCLUSION

Recently, some studies have indicated that particles in the large-scale jets of radio galaxies could be accelerated to high energies through stochastic acceleration (e.g. Hardcastle et al. 2008; O’Sullivan et al. 2009). Actually, stochastic acceleration has been applied to explain the emissions from the inner jets of blazars (e.g. Wang 2002; Katarzyński et al. 2006b; Tramacere et al. 2011). It is likely that several acceleration mechanisms might be acting in parallel in the jets of AGNs (e.g. Rieger, Bosch-Ramon & Duffy 2007). Because of the detections of X-ray and GeV emissions from the extended jets of blazars and radio galaxies (e.g. Abdo et al. 2010b; Massaro et al. 2011), we think it is worth investigating whether TeV emission could be created in the extended jet of a blazar. In this paper, we have assumed that electrons in the extended jet of 1ES 1101–232 can be accelerated to high energies by stochastic acceleration. Therefore, TeV emission might be produced via Compton upscattering of CMB and EBL photons by these electrons. The traditional emission from the inner jet should also be taken into account. For simplicity, we use the conventional SSC model to produce this emission from the inner jet. It can be seen that our model can reproduce the SED of 1ES 1101–232 well, and its hard TeV emission is dominated by the IC/CMB component from the extended jet. Because our model needs the extent of the emission region in the extended jet to be on a kiloparsec scale, there cannot be any substantial TeV variability. The emissions from a compact region in the inner jet make a dominant contribution to the emission of 1ES 1101–232 at the optical–X-ray and GeV band. Therefore, the variabilities on time-scales of days at the optical–X-ray and GeV band are allowed. If it is determined that the extended jet is another TeV emission region, this fact will provide stronger constraints on the physical properties of the emission region in the inner jet. However, it should be kept in mind that this model is only applicable for TeV blazars that show no TeV variability (e.g. 1ES 1101–232, 1ES 0229+020 and 1ES 0347+290).

We have assumed three characteristic values of the Doppler factor for the TeV emission region in the extended jet. We can reproduce the TeV emission of 1ES 1101–232 well by using each of these values. Furthermore, for a moderate or a large value of the Doppler factor (i.e. \(\delta_0 \sim 10\) and \(15\)), the physical parameters in the TeV-emitting region in the extended jet are consistent with the equipartition (or quasi-equipartition). In contrast, for a small value of \(\delta_0 \sim 5\), the parameters largely depart from the equipartition with \(U'_p/U'_b \gg 1\). Piner et al. (2010) have suggested that the bulk Lorentz factors in the TeV emission region and radio emission region of TeV blazars could be different. Therefore, from our results, we conclude
that the TeV-emitting region in the extended jet of 1ES 1101–232 should be moderately or highly beamed.

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