Emitting electron spectra and acceleration processes in the jet of PKS 0447–439

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Abstract

We investigate the electron energy distributions (EEDs) and the corresponding acceleration processes in the jet of PKS 0447–439, and estimate its redshift through modeling its observed spectral energy distribution (SED) in the frame of a one-zone synchrotron-self Compton (SSC) model. Three EEDs formed in different acceleration scenarios are assumed: the power-law with exponential cut-off (PLC) EED (shock-acceleration scenario or the case of the EED approaching equilibrium in the stochastic-acceleration scenario), the log-parabolic (LP) EED (stochastic-acceleration scenario and the acceleration dominating), and the broken power-law (BPL) EED (no acceleration scenario). The corresponding fluxes of both synchrotron and SSC are then calculated. The model is applied to PKS 0447–439, and modeled SEDs are compared to the observed SED of this object by using the Markov Chain Monte Carlo method. The results show that the PLC model fails to fit the observed SED well, while the LP and BPL models give comparably good fits for the observed SED. The results indicate that it is possible that a stochastic acceleration process acts in the emitting region of PKS 0447–439 and the EED is far from equilibrium (acceleration dominating) or no acceleration process works (in the emitting region). The redshift of PKS 0447–439 is also estimated in our fitting: $z = 0.16 \pm 0.05$ for the LP case and $z = 0.17 \pm 0.04$ for BPL case.

Key words: acceleration of particles — BL Lacertae objects: individual (PKS 0447–439) — galaxies: distances and redshifts

1 Introduction

PKS 0447–439, a high-frequency peaked BL Lac object (HBL), is one of the brightest sources observed by the Large Area Telescope (LAT) instrument on board the Fermi telescope. Motivated by the Fermi/LAT observation, the H.E.S.S. Imaging Atmospheric Cherenkov Telescope observed PKS 0447–439 between 2009 November and 2010 January for 3.5 hr in total. During the H.E.S.S. campaign, Swift observed PKS 0447–439 at optical–X-ray bands for about one week (Abramowski et al. 2013). Therefore, a high-quality multi-band spectral energy distribution (SED) has been built (Prandini et al. 2012; Abramowski et al. 2013). However, the redshift of PKS 0447–439 has not yet been determined due to its weak emission lines. Its redshift has been measured by many authors with different methods. Craig and Fruscione (1997) gave an estimate of its redshift as $z = 0.107$. Perlman et al. (1998) reported a value of $z = 0.205$ based on a very weak spectral feature, which was interpreted as the Ca line (lately considered doubtful). Landt and Bignall (2008) gave a lower limit of 0.176. Recently, Landt (2012) suggested a high lower limit of $z > 1.246$ based on the weak absorption lines which, however, were identified as atmospheric absorption lines.
by the detection of Pita et al. (2012). On the other hand, the redshift of PKS 0447–439 can be estimated through combining its observed GeV–TeV spectrum; for example, Prandini et al. (2012) suggested that its redshift is likely 0.2, and Abramowski et al. (2013) pointed out that the most conservative upper limit of this object is \( z < 0.59 \).

It is well known that the multi-band emission from a blazar with synchrotron peak in the UV–X-ray bands (HBL) can be explained in the frame of a one-zone SSC model (e.g., Tavecchio et al. 1998; Finke et al. 2008; Zhang et al. 2012). In this model, the SED for a blazar consists of two bumps; the first bump can be explained by synchrotron emission of relativistic electrons, and the second bump could be produced by relativistic electrons inverse Compton (IC) scattering with photons which come from synchrotron emission (synchrotron self-Compton, SSC; e.g., Rees 1967; Maraschi et al. 1992). Note that besides the classic one-zone model, a kind of two-zone (acceleration zone and cooling zone) model has been proposed (e.g., Kirk et al. 1998; Kusunose et al. 2000; Fan et al. 2008; Weidinger et al. 2010; Weidinger & Spanier 2010). Here, we will focus on the one-zone SSC model.

In modeling the SED of a blazar in the one-zone SSC model, an important physical quantity is the emitting electron distribution (EED). The form of EED can give information about acceleration and cooling processes. Generally, there are three kinds of EED formed in different scenarios. The first one is the power-law with exponential cut-off (PLC) EED, which is usually believed to be formed in the Fermi I acceleration process (shock acceleration; e.g., Drury et al. 1994; Kirk et al. 1998; Kusunose et al. 2000). However, recent studies indicate that the PLC can also be obtained in a scenario where Fermi II (or both Fermi I and Fermi II) acceleration processes act in the case of EED approaching equilibrium (e.g., Weidinger et al. 2010; Tramacere et al. 2011; Yan et al. 2012). The second one is the log-parabolic (LP) EED, which can be formed in the Fermi II acceleration process (stochastic acceleration) in the case where the acceleration process dominates over radiative cooling (e.g., Becker et al. 2006; Tramacere et al. 2011). The third one is that no acceleration process is considered in the emitting region, the injected EED can indicate the acceleration process (e.g., Chiaberge & Ghisellini 1999; Kataoka et al. 2000; Li & Kusunose 2000; Böttcher & Chiang 2002; Chen et al. 2011, 2012) and the EED can be approximated by a broken power law (BPL; e.g., Dermer & Menon 2009; Böttcher et al. 2013; Finke 2013). Many authors have studied the emission mechanisms in the three scenarios by using time-dependent models (e.g., Böttcher & Chiang 2002; Tramacere et al. 2011; Zheng & Zhang 2011; Yan et al. 2012). For simplicity we use static EEDs here. In a simplified one-zone SSC model, the EEDs and acceleration processes in the jet of the HBL can be investigated through modeling the high-quality SED (e.g., Yan et al. 2013).

In this work, after assuming three EEDs formed in the three scenarios described above, we investigate the EEDs and acceleration processes in the jet of PKS 0447–439 through fitting its quasi-simultaneous SED with a simplified one-zone SSC model. In order to obtain more efficient constraints on the model parameters, we employ the MCMC method to investigate the high-dimensional model parameter spaces systematically. The redshift of PKS 0447–439 is also estimated in the fitting. We adopt the cosmological parameters \((H_0, \Omega_m, \Omega_{\Lambda}) = (70 \text{ km s}^{-1} \text{Mpc}^{-1}, 0.3, 0.7)\) throughout this paper.

2 Modelling SED

We will model the SED in the frame of a one-zone SSC model given by Finke, Dermer, and Böttcher (2008). In this model, the non-thermal multi-wavelength emission is assumed to be produced by both the synchrotron radiation and SSC process of relativistic electrons in a homogeneous blob of the jet, 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. There are three model parameters characterizing the global properties of the blob: the magnetic field intensity in the emitting blob \(B\), the Doppler factor \(\delta_D\), and the radius of the blob \(R'_b = t_{v_{\min}} / (1 + z)\), where \(t_{v_{\min}}\) is the minimum variability timescale in the observer’s frame. Here, quantities in the observer’s frame are unprimed, and quantities in the comoving frame are primed. Note that the magnetic field \(B\) is defined in the comoving frame, despite being unprimed.

2.1 Emitting electron distributions

For the relativistic electron distribution in the blob, the three cases we described in section 1 are considered. If there exists an acceleration process in the emitting blob, two forms of EEDs (PLC and LP) could be generated. The PLC electron distribution is

\[
N'(\gamma') \sim \left(\frac{\gamma'}{\gamma_c'}\right)^{-s} \exp \left(-\frac{\gamma'}{\gamma_c'}\right) \quad \text{for} \quad \gamma'_{\min} \leq \gamma' \leq \gamma'_{\max},
\]

where \(s\) is the electron energy spectral index, and \(\gamma_c'\) is the high-energy cut-off. The LP EED generated in the framework of stochastic-turbulence acceleration is

\[
N'(\gamma') \sim \begin{cases} 
\left(\frac{\gamma'}{\gamma_c'}\right)^{-s} & \gamma'_{\min} \leq \gamma' \leq \gamma'_{c} \\
\left(\frac{\gamma'}{\gamma_c'}\right)^{[s + \log(\frac{\gamma_c'}{\gamma_c})]} & \gamma_c \leq \gamma' \leq \gamma'_{\max}.
\end{cases}
\]
where \( r \) is the curvature term of the EED (Massaro et al. 2006). In the above two cases, \( \gamma'_c \) is determined by the competition between the acceleration process and the energy losses of electrons. The spectral index \( s \) is controlled by the acceleration and escape timescales, \( t_{acc} \) and \( t_{esc} \), or the duration of the injection (impulsive or continuous; e.g., Katarzyński et al. 2006).

If there is no acceleration process in the emitting blob, the cooled EED in the blob is the BPL shape. Here, we use the BPL electron distribution given by Dermer, Finke, and Krug (2009), i.e.,

\[
N'_\gamma(\gamma') \sim H(\gamma'; \gamma'_\text{min}, \gamma'_\text{max}) \left[ \gamma'^{-p_1} \exp(-\gamma'/\gamma'_0) \times H((p_2 - p_1)\gamma'_0 - \gamma') \right] + \left\{(p_2 - p_1)\gamma'_0\right\}^{p_2-p_1} \gamma'^{-p_2} \times \exp(p_1 - p_2) H(\gamma' - (p_2 - p_1)\gamma'_0),
\]

where \( H(x; x_1, x_2) = 1 \) for \( x_1 \leq x \leq x_2 \) and \( H(x; x_1, x_2) = 0 \) everywhere else; as well as \( H(x) = 0 \) for \( x < 0 \) and \( H(x) = 1 \) for \( x \geq 0 \). \( \gamma'_\text{min} \) and \( \gamma'_\text{max} \) are the minimum and maximum energies of electrons, respectively. \( p_1 \) and \( p_2 \) are the spectral indices below and above the electron’s break energy \( \gamma'_0 \). In this case, \( \gamma'_0 \) is determined by the energy losses and escape of electrons. The injection process (i.e., the injected spectrum and the injection time) and evolution time determines \( p_1 \) and \( p_2 \). Note that only when the \( \gamma'_c \) of the injected EED \( \gg \gamma'_0 \), which means significant energy losses, can the cooled EED be the BLP shape distinctly. In all of the three cases, we use the factor \( U'_e/U'_b \) to normalize the electron numbers in the emitting blob.

### 2.2 Synchrotron and SSC fluxes

The synchrotron flux and the SSC flux are calculated as in Finke, Dermer, and Bötcher (2008). The synchrotron flux is

\[
vF_{\nu, \text{syn}} = \frac{\sqrt{3}\gamma^3}{4\pi} \frac{e^3 B^2}{b dL^2} \int_0^\infty d\gamma' N'_\gamma(\gamma')(4\pi R_b^3/3) R(x),
\]

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

\[
u'_\text{syn}(\nu) = \frac{R_b^3 \sqrt{3} \gamma^3 B^2}{c b dL^2} \int_0^\infty d\gamma' N'_\gamma(\gamma')(4\pi R_b^3/3) R(x).
\]

The SSC flux is

\[
vF_{\nu, \text{SSC}} = \frac{3}{4} c \sigma_T \epsilon_0^2 \frac{b^3}{4\pi dL^2} \int_0^\infty d\epsilon' \frac{\nu'_\text{syn}(\epsilon')}{\epsilon'^2} \times \int_{\nu'_\text{min}}^{\nu'_\text{max}} d\nu' \left( \frac{N'_\gamma(\nu')(4\pi R_b^3/3)}{\gamma'^2} \right) F_C(\nu', \Gamma'),
\]

where \( \sigma_T \) is the Thomson cross section, \( m_e c^2 \epsilon_0 = bh(1 + z)/\delta_D \) is the energy of IC-scattered photons in the comoving frame,

\[
F_C(\nu', \Gamma') = 2q' \ln q' + (1 + 2q')(1 - q') + \frac{q'^2 \Gamma'^2}{2(1 + q' \Gamma')^2} (1 - q'),
\]

\[
q' = \frac{\epsilon'/\gamma'}{\Gamma'_c (1 - \epsilon'/\gamma')},
\]

\[
\Gamma'_c = 4\epsilon' \gamma',
\]

and

\[
\frac{1}{4 \gamma'^2} \leq q' \leq 1.
\]

Very high energy (VHE) photons emitted by blazars are effectively absorbed through the pair-production process, by interaction with extragalactic background light (EBL: e.g., Stecker et al. 1992). The absorption effect depends on both the EBL photon density and the redshift of the TeV source. EBL is mainly composed of stellar light and the reprocessed emission produced by stellar dust. Due to the bright foreground (e.g., the zodiacal light and the stellar light from the Milky Way), direct measurements of the EBL become very difficult. Thus, many EBL models are proposed, such as Stecker, Malkan, and Scully (2006), Franceschini, Rodighiero, and Vaccari (2008), Razzaza, Dermer, and Finke (2009), Finke, Razzaza, and Dermer (2010), Kneiske and Dole (2010), Dominguez et al. (2011), Gilmore et al. (2012), Inoue et al. (2013). In this work we use the EBL model of Finke, Razzaza, and Dermer (2010), which is believed to be correct to a high confidence level (Ackermann et al. 2012), to correct the EBL absorption.

### 2.3 Fitting method

Because the MCMC method which is based on Bayesian statistics is more efficient for sampling of the parameter spaces, it has frequently been used to fit the SEDs of blazars and supernova remnants (SNRs) in order to investigate high-dimensional parameter spaces (e.g., Yuan et al. 2011; Yan et al. 2013). In this MCMC method the Metropolis–Hastings sampling algorithm, which ensures that the probability density functions of model parameters can be asymptotically approached with the number density of samples, is
Table 1. The marginalized best-fit model parameters, their 68% confidence limits and the reduced $\chi^2$ values for three EEDs.

<table>
<thead>
<tr>
<th>Model</th>
<th>$z$</th>
<th>$\gamma^\prime_{\min}$</th>
<th>$s$, $r$, $p_2$</th>
<th>$B$</th>
<th>$\tau_{r, \min}$</th>
<th>$\delta_D$</th>
<th>$U_e^\prime/U_B^\prime$</th>
<th>$\chi^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PLC model</td>
<td>0.10</td>
<td>8.99</td>
<td>2.70</td>
<td>0.50</td>
<td>5.86</td>
<td>2.81</td>
<td>58.45</td>
<td>1.48</td>
</tr>
<tr>
<td>68% limit</td>
<td>(0.69–0.13)</td>
<td>(8.24–10.00)</td>
<td>(2.65–2.74)</td>
<td>(0.40–0.59)</td>
<td>(4.19–7.53)</td>
<td>(2.40–5.0)</td>
<td>(55.11–62.56)</td>
<td>—</td>
</tr>
<tr>
<td>LP model</td>
<td>0.16</td>
<td>0.59</td>
<td>0.76</td>
<td>0.29</td>
<td>5.79</td>
<td>4.11</td>
<td>63.83</td>
<td>0.49</td>
</tr>
<tr>
<td>68% limit</td>
<td>(0.11–0.21)</td>
<td>(0.38–0.81)</td>
<td>(0.65–0.87)</td>
<td>(0.17–0.44)</td>
<td>(3.46–8.60)</td>
<td>(3.37–5.0)</td>
<td>(34.73–93.58)</td>
<td>—</td>
</tr>
<tr>
<td>BPL model</td>
<td>0.17</td>
<td>3.33</td>
<td>4.26</td>
<td>0.30</td>
<td>5.42</td>
<td>4.22</td>
<td>61.09</td>
<td>0.16</td>
</tr>
<tr>
<td>68% limit</td>
<td>(0.13–0.21)</td>
<td>(2.70–3.91)</td>
<td>(4.10–4.42)</td>
<td>(0.18–0.43)</td>
<td>(2.86–8.60)</td>
<td>(3.58–5.0)</td>
<td>(35.02–85.89)</td>
<td>—</td>
</tr>
</tbody>
</table>

In this work, we adopt the quasi-simultaneous SED of PKS 0447–439 reported in Prandini et al. (2012), which includes the Swift/UVOT, Swift/XRT, Fermi/LAT, and H.E.S.S. data observed during 2009 November–2010 January. In our fittings, we fix $\gamma^\prime_{\min} = 400$ and $\gamma^\prime_{\max} = 10^8$ for the three cases. Meanwhile, we use $\tau_{r, \min} = 1$ d as its upper limit because of a signature of variability at X-ray energies on a timescale of one day (Prandini et al. 2012). We also set an upper limit for the Doppler factor, $\delta_D \leq 50$, to avoid the extreme value. In our fittings, the redshift is taken as a free parameter since the redshift of an HBL can be constrained through fitting its SED including the GeV and TeV data (e.g., Acciari et al. 2010; Abdo et al. 2011; Yan et al. 2013; Abramowski et al. 2013). In this method of estimating the redshift, the intrinsic VHE spectrum is obtained by fitting the observed SED covering from optical to GeV energies. Through comparing the EBL corrected intrinsic VHE spectrum (depending on the redshift) and the observed VHE spectrum, the redshift can be inferred (Acciari et al. 2010; Yan et al. 2013).

The SED modeling results are shown in figure 1. The marginalized best-fit parameter values and their 68% confidence limits are summarized in table 1. The marginalized one-dimensional (1D) probability distributions of the model parameters are shown in figure 2 (the PLC case), figure 3 (the LP case), and figure 4 (the BPL case).
For the BPL case, we also fix $p_1 = 2.0$ and there are also seven parameters, which are $B$, $\delta_D$, $t_{\nu, \text{min}}$, $P_\nu$, $\gamma'_c$, $U_c/U_B$, and $z$ (see table 1). In this case, the fitting (the dashed line in figure 1) compares well with that in the LP case. The constraints on the parameters are almost the same as those in the LP case. In this case, the redshift is also constrained well, with $z = 0.17 \pm 0.04$.

4 Discussion and conclusions

Using the MCMC method, we fitted the SED of PKS 0447–439 in the one-zone SSC model for three kinds of EEDs having clear physical meanings: PCL, LP, and BPL EEDs. Our results show that the SED of PKS 0447–439 can be fitted well for LP and BPL EEDs. As mentioned in section 1, the LP shape EED can be formed in the stochastic acceleration process when the acceleration timescale is shorter than the cooling timescale. The BPL shape EED can be formed in the emitting blob where no acceleration process works, and the broken energy $\gamma'_c$ is determined when the cooling timescale is equal to the escape timescale. Our results indicate that the multi-band emissions of PKS 0447–439 originate in a blob where either the stochastic acceleration dominates over the cooling or no acceleration process works. It can be inferred from figure 1 (according to the peak fluxes of the synchrotron and SSC components) that the synchrotron cooling is comparable to the SSC cooling. The synchrotron time is $t_{\text{syn}} \approx 7.8 \times 10^8 / (\gamma' B^2)$. In the LP case, taking $\gamma' = \gamma'_c$, we obtain $t_{\text{syn}} \approx 1.6 \times 10^8$ s. Hence, in the stochastic acceleration case the acceleration timescale should be less than $\sim 10^8$ s. The inefficient cooling is attributed to the small magnetic field strength and then the low synchrotron photon density, and in this case a relatively large size of blob is required ($R'_b \approx 7.2 \times 10^{16}$ cm). It is hard to distinguish LP EED from BPL EED based on the current observations. In figure 1, however, we note that the case of BPL predicts higher $\nu F_\nu$ fluxes at $\sim 20–50$ keV than the fluxes predicted in the case of LP. Therefore, the observations of The Nuclear Spectroscopic Telescope Array (NuSTAR: Harrison et al. 2013) at 6–80 keV may be helpful to distinguish the BLP scenario from the LP scenario. The alternative way to distinguish the BLP scenario from the LP scenario may be the observed minimum variability timescale $t_{\nu, \text{min}}$, since our fitting results show that $t_{\nu, \text{min}} > 2.86 \times 10^4$ s for BLP EED while $t_{\nu, \text{min}} > 3.46 \times 10^4$ s for LP EED. Our results can be used as a preliminary indicator for detailed studies of the acceleration processes in the jet to simplify the physical model and reduce the model parameters.

Due to the weak emission line of the HBL, the classical spectrographic measurement of redshift is sometimes invalid. Thanks to the observations in the GeV and TeV...
bands, an alternative method for estimating the redshift of the HBL is to fit its GeV–TeV spectrum with the certain emission model (e.g., Acciari et al. 2010; Abdo et al. 2011; Yan et al. 2013). With a more powerful MCMC method, our results show that in the frame of the one-zone SSC model, the redshift of PKS 0447–439 is between 0.11 and 0.21, and the most likely redshift is 0.16 and 0.17, which are basically consistent with the results estimated by other authors with different methods (e.g., Perlman et al. 1998; Landt & Bignall 2008; Prandini et al. 2012; Abramowski et al. 2013). There is no discrepancy between the redshift derived in the LP case and BPL case. Our results depend on the EBL model. A recent believable study indicated that the real EBL intensity may be slightly weaker than the prediction of the EBL model of Finke, Razzaque, and Dermer (2010), which should be scaled by the factor 0.86 ± 0.23 (Ackermann et al. 2012). We found that when the EBL model of Finke, Razzaque, and Dermer (2010) is scaled by the factor 0.86, the estimate of the redshift is not changed.

We note that the jet of PKS 0447–439 appears to be particle dominated (U_e/\U_B ≈ 60; see table 1). It seems that the jets of the HBLs (e.g., Mrk 421 and Mrk 501) whose high-energy emissions can be explained with one component tend to be particle dominated (e.g., Mankuzhiyil et al. 2012; Yan et al. 2013; Zhang et al. 2013), while the jets of flat spectrum radio quasars (FSRQs; e.g., 3C 279) whose high-energy emissions require multi-component origination could tend to achieve equipartition between the energies of emitting electrons and magnetic field (e.g., Dermer et al. 2013; Zhang et al. 2013). More considerations are needed on this issue.

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