Convex X-ray Spectra of PKS 2155-304 and Constraints on the Minimum Electron Energy

Sitha K. Jagan1*, S. Sahayanathan2 †, Frank M. Rieger3,4 ‡ and C. D. Ravikumar1

1Department of Physics, University of Calicut, Malappuram-673635, India
2Astrophysical Sciences Division, Bhabha Atomic Research Centre, Mumbai - 400085, India
3ZAH, Institute of Theoretical Astrophysics, University of Heidelberg, Philosophenweg 12, 69120 Heidelberg, Germany
4Max-Planck-Institut für Kernphysik, P.O. Box 103980, 69029 Heidelberg, Germany

ABSTRACT

The convex (concave upward) high-energy X-ray spectra of the blazar PKS 2155-304, observed by XMM-Newton, is interpreted as the signature of sub-dominant inverse Compton emission. The spectra can be well fitted by a superposition of two power-law contributions which imitate the emission due to synchrotron and inverse Compton processes. The methodology adopted enables us to constrain the photon energy down to a level where inverse Compton emission begins to contribute. We show that this information supplemented with knowledge of the jet Doppler factor and magnetic field strength can be used to constrain the low-energy cutoff \( \gamma_{\text{min}} \) of the radiating electron distribution and the kinetic power \( P_1 \) of the jet. We deduce these quantities through a statistical fitting of the broadband spectral energy distribution of PKS 2155-304 assuming synchrotron and synchrotron self-Compton emission mechanisms. Our results favour a minimum Lorentz factor for the non-thermal electron distribution of \( \gamma_{\text{min}} \gtrsim 60 \), with a preference for a value around \( \gamma_{\text{min}} = 330 \). The required kinetic jet power is of the order of \( P_1 \sim 3 \times 10^{45} \text{ erg s}^{-1} \) in case of a heavy, electron-proton dominated jet, and could be up to an order of magnitude less in case of a light, electron-positron dominated jet. When put in context, our best fit parameters support the X-ray emitting part of blazar jets to be dominated by an electron-proton rather than an electron-positron composition.

Key words: acceleration of particles – radiation mechanisms: non-thermal – galaxies: BL Lacertae objects: individual: PKS 2155-304 – X-rays: galaxies – X-rays: individual: PKS 2155-304

1 INTRODUCTION

A prominent morphological feature of the radio-loud type AGN is the presence of relativistic jets extending up to megaparsec scales. Blazars are the class of radio-loud AGN in which the jet is aligned close to the line of sight of the observer. Hence the emission from blazars is significantly Doppler-boosted. Their spectrum is predominantly non-thermal in nature, extending from radio to GeV and TeV energies (e.g., Abdo et al. 2010; Reimer & Böttcher 2013). Blazars are further classified into flat spectrum radio quasars (FSRQs) or BL Lac type objects (BL Lacs) depending upon the presence or absence of emission line features. The spectral energy distribution (SED) of blazars is typically characterized by a double-hump structure with the low-energy component peaking around IR/optical/UV energies and the high-energy component peaking around gamma-ray energies (e.g., Fossati et al. 1998; Ghisellini et al. 2017). The low-energy emission is well understood to be synchrotron emission from a relativistic non-thermal electron distribution; whereas, the high-energy emission is often interpreted as due to inverse Compton (IC) scattering of low-energy photons by the same electron distribution (e.g., Maraschi et al. 1992; Marscher & Gear 1985; Begelman et al. 1987; Dermer & Schlickeiser 1993). The peak energy of the synchrotron spectral component is used to sub-divide BL Lacs into low energy peaked BL Lacs (LBLs: peaking at IR/optical), intermediate energy peaked BL Lacs (IBLs: peaking at optical/UV) and high energy peaked BL Lacs (HBLs: peaking at UV/soft X-ray) (Padovani & Giommi 1995; Fossati et al. 1998). Within the leptonic framework, the gamma-ray spectra of HBLs are well reproduced by synchrotron self-Compton (SSC) emission. The target photons for the IC scattering in this case are the synchrotron photons themselves.

Spectral modelling of HBLs by synchrotron and SSC processes suggests that the underlying electron distribution may be closely related to a power-law/broken power-law type function resulting from Fermi acceleration and radiative cooling processes (e.g., Kirk et al. 1998; Kirk & Mastichiadis 1999). However, high resolution X-ray spectra can exhibit significant deviations from a power-law and are often better reproduced by a log-parabola function (Massaro et al. •}
madejski et al. 2016; Ghisellini et al. 2014; Zdziarski & Bottcher 2015). Though the detection of neutrinos provides indications for the presence of hadrons in blazar jets (IceCube Collaboration et al. 2018; Tavecchio et al. 2014); their signature in the emission spectra is largely unknown since models advocating a hadronic origin of high-energy spectra pose serious energy constraints (Zdziarski & Bottcher 2015). Leptonic models are largely successful in explaining the broadband SED of blazars especially during the flare. These models generally assume the protons to be cold and contribute only to the jet kinetic power (Ghisellini et al. 2014). However, if their number is equal to that of the non-thermal electrons (heavy jet), the predicted jet power could exceed the accretion disk luminosity (Ghisellini et al. 2014).

For a power-law or power-law type electron distribution $N(y) = \gamma > 1$, the total electron number density $N_{\text{tot}}$ is determined by the differential number density at the minimum cut-off energy $\gamma_{\text{min}}$, i.e., $N_{\text{tot}} \approx N(\gamma_{\text{min}}) / (\gamma - 1)$, $\gamma$ being the electron Lorentz factor. Under a Fermi-type acceleration process, this energy can be related to the energy of the electron population injected into the acceleration region (Kirk et al. 1998; Kusunose & Takahara 2018). As mentioned earlier, the knowledge of the total electron number density can also provide an estimate of the blazar jet mass density by assuming an appropriate fraction of hadrons. This, along with broadband spectral modelling, can provide clues on the kinetic power of blazar jets. However, the estimation of $\gamma_{\text{min}}$ based on spectral information is complicated by the fact that the related synchrotron emission usually falls into the radio regime which is significantly self-absorbed or contaminated by extended jet emission. On the other hand, the low-energy IC contribution may be overwhelmed by the dominant synchrotron emission. Still, an upper limit on the related minimum IC photon energy might be estimated from the transition energy in the broadband spectra, where the dominant contribution shifts from synchrotron to IC emission (Kataoka & Stawarz 2016).

PKS 2155-304 is a HBL located at a redshift of $z = 0.116$ and well observed from radio to very high energy (VHE) gamma rays. Its synchrotron spectrum peaks at UV and the IC spectral component peaks at GeV energies (Zhang 2008; Madejski et al. 2016). Its broadband spectra can be reproduced reasonably well by synchrotron and SSC emission of a broken power-law type electron distribution (Madejski et al. 2016; Abdalla et al. 2020). The source is known to exhibit rapid variability with doubling time as short as a few minutes, suggesting that the emission region is located very close to the supermassive black hole powering the AGN (Aharonian et al. 2007; Rieger & Volpe 2010).

The mild curvature observed in the high resolution X-ray spectra can be interpreted as an outcome of the energy-dependence of the particle escape time-scale. However, during certain epochs, the X-ray spectral curvature reverses the sign indicating a convex (concave upward) spectrum suggesting the spectral contribution of a sub-dominant IC component in addition to the synchrotron component (Jagan et al. 2018).

The contribution of IC emission to the X-ray spectra of PKS 2155-304 can be inferred from XMM-Newton observation, where the spectrum has been found to harden beyond 4 keV. This was first shown by Zhang (2008), who used a broken power-law spectral fit to highlight the presence of an IC component. NuSTAR observations of PKS 2155-304 at 0.5-60 keV also reveal that the IC spectral component dominates over the synchrotron spectrum beyond $\approx 6$ keV (Madejski et al. 2016). This has been demonstrated by fitting the spectrum with a broken power-law, a combination of two power-law functions (double power-law) and log parabola–power-law combination, respectively. NuSTAR observation of yet another HBL, MKN 421 also showed a convex X-ray spectrum during a low-flux state that can be well reproduced by a double power-law function (Kataoka & Stawarz 2016). In general, the presence of convex X-ray spectra has also been witnessed for many IBls and LBLs and are interpreted as the signature of the IC spectral component (e.g., Tagliaferri et al. 2000; Tanihata et al. 2003; Wierzcholska & Wagner 2016; Gaur et al. 2018).

Alternatively, a convex X-ray spectrum may also be an outcome of a high energy pile-up of the emitting electron distribution. Such a high energy excess in the electron distribution can occur in at least two scenarios. When the confinement time of the electrons in the region of particle acceleration is much longer than the radiative loss timescales, the electrons will eventually get accumulated at the maximum energy giving rise to a relativistic Maxwellian tail at high energies (e.g., Schlickeiser 1985; Ostrowski 2000; Stawarz & Petrosian 2008; Lefa et al. 2011). Another scenario could be, when the electron energy loss rate at high energy is dominated by IC scattering of the external photon field happening in the Klein-Nishina regime (Dermer & Atoyan 2002; Moderski et al. 2005).

While in the case of PKS 2155-304 the high energy emission is thought to be dominated by SSC processes rather than external Compton, it is often not straightforward to differentiate the process responsible for the convex X-ray spectra. Nevertheless, the contribution of a sub-dominant Compton spectral component can be identified through a statistical study between the X-ray spectral curvature and the simultaneous low energy gamma-ray spectral index of the Compton spectrum.

In the present work, we perform a detailed study of the convex X-ray spectra of PKS 2155-304 observed by XMM-Newton. The convexness observed in the 0.6-10 keV X-ray spectrum is interpreted as the signature of a sub-dominant SSC contribution. We extend this along with broadband spectral modelling to constrain the low-energy cut-off of the emitting electron distribution and the source energetics.

The paper is organised as follows: In § 2, we explain the observations and data reduction procedure. Epochs during which the X-ray spectrum is convex are identified in § 3. In § 4 and 5, we show that this can be interpreted as the result of a combination of synchrotron and SSC spectral components using a double power-law function. In § 6 we describe the broadband spectral fitting of the source and the estimation of jet power. The outcome is discussed in § 7. Throughout this work, we adopt a cosmology with $\Omega_m = 0.3$, $\Omega_{\Lambda} = 0.7$ and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$.

2 OBSERVATIONS AND DATA REDUCTION

PKS 2155-304 has been observed extensively by XMM-Newton, with 37 XMM-Newton master observations available in the HEASARC archive from 2000-2014. For our X-ray study, we have taken the XMM-Newton’s European Photon Imaging Camera (EPIC)-PN data only and avoided EPIC-MOS data. The reason for this being less sensitivity and quantum efficiency, and the chance of
pile up in EPIC-MOS data during the observation of bright sources. Among 37 XMM-Newton observations, only 22 PN observations were available during which the camera was operated in the small window imaging mode. The XMM-Newton Science Analysis System (SAS version 14.0) with the latest calibration files was used for the data reduction.

The standard procedures were followed to reprocess the Observation Data File (ODF). The XMM-Newton SAS pipeline command epchain is used to produce the calibrated photon event files for the PN camera. In the selected 0.2-10.0 keV energy range, we considered both single and double events (PATTERN≤ 4) of PN data which were flagged good quality (FLAG=0) for processing. We extracted the light curves in the high energy range 10-12 keV in order to check the background particle flaring. An appropriate threshold rate was chosen from the light curve to omit the background flaring period and a “good time interval (GTI)” event list was created. A circular region of size 40″ around the source was selected for extracting the source spectrum and two circular regions of the same size were chosen as the background. These background regions were selected from the same CCD chip of source region such that the source photon contribution was negligible within these regions.

The chance of pile up is more probable for bright sources like PKS 2155-304 and hence, we used the SAS task epatplot to examine the pile up effect in all observations. We found that certain observations are affected by the pile up. In order to avoid these pile up effects, we considered an annulus region around the bright source with an inner radius of 10″ and outer radius varying from 38″ to 40″. The range of the outer radius was chosen such that the source selection region remained within the frame of the CCD chip. Only the annulus region was taken into account for source count extraction and the inner region was excluded.

The SAS tool specgroup was used for grouping the spectral channels. We imposed a condition of having minimum 100 counts in each group. PKS 2155-304 being a bright source, there can be large number of counts in the spectrum which in turn results in large number of bins. To avoid the chance of oversampling, we fixed the oversampling value to 5 so that the energy resolution cannot be covered by more than 5 grouped bins. The Galactic hydrogen column density (N_H = 1.71 × 10^{20} cm^{-2}) toward PKS 2155-304 was kept constant for all spectral fits (Bhagwan et al. 2014).

We also used the simultaneous optical observation of the source by Optical Monitor (OM) onboard XMM-Newton. Reprocessing of the OM data was carried out by the SAS metatask omitchain. From the combined source list, our source of interest was obtained by cross matching its RA and Dec with the coordinates of all sources in the list. Unlike X-rays, optical/UV photons from the jet can be contaminated by the galactic photons at the same wavelength. This was treated as systematic error, and similar to Jagan et al. (2018), it was estimated by fitting the optical/UV data by a power-law function. We found that adding 3 per cent systematic error in most of the data sets led to a better fit statistics. However, we had to reject 6 observations which either demanded higher systematic errors or lacked a minimum of 3 optical/UV flux points to perform the statistical fit. Finally, we got 16 observations which are used for the present study. Among these observations we selected only those observations which showed convex X-ray spectra (see § 3). The details of these observations are given in Table 3. The Galactic reddening correction was done for all the optical/UV data using the model UVM2 and fixing the parameter E_B-V = 0.019 (Seaton 1979; Schlafly & Finkbeiner 2011).

3 X-RAY SPECTRAL CURVATURE

To identify the X-ray spectral curvature of PKS 2155-304, the 22 epochs of XMM-Newton PN observations over the energy range 0.6-10.0 keV were fitted with the X-ray Spectral Fitting Package (XSPEC) (Arnaud 1996) using a log-parabola function (Massaro et al. 2004). This function is defined as

$$F_{\text{lp}}(\epsilon) = F_p \left( \frac{\epsilon}{\epsilon_p} \right)^{-\alpha - \beta \log(\epsilon/\epsilon_1)},$$

(1)

where $\epsilon$ is the photon energy (keV), $F_p$ is the flux (photons cm^{-2} s^{-1} keV^{-1}) at photon energy $\epsilon_p$ and the spectral shape is determined by the two parameters $\alpha$ and $\beta$. The parameter $\alpha$ governs the spectral slope at $\epsilon_p$ and $\beta$ is the parameter defining the spectral curvature. A negative value of $\beta$ indicates a convex spectrum that could hint at the presence of Compton spectral component or a high energy excess in the underlying electron distribution. In the 0.6-10.0 keV regime the spectrum of PKS 2155-304 is dominated by the high energy end of the synchrotron emission, so that any IC contribution can result in mild negative value of $\beta$.

The log-parabola spectral fit to most of the observations resulted in positive $\beta$ suggesting a convex spectrum (Jagan et al. 2018). Among the 22 observations, four (IDs 0158961401, 0411780101, 0411782021 and 0411787070) have negative $\beta$ values indicative of a convex nature. The best fit parameters during these epochs are given in Table 1. For three observations (0158961401, 0411780101 and 0411782021) the negative values of $\beta$ are statistically significant.

4 COMPTON SPECTRAL SIGNATURE IN X-RAY SPECTRA

To explore the contribution of a Compton component in the X-ray spectra of PKS 2155-304, we assume that the synchrotron and SSC spectra at 0.6-10.0 keV can each be represented by a power-law. Accordingly, the cumulative spectrum ($\nu F_\nu$) will be a double power-law function defined by

$$F_{\text{dp}}(\epsilon) = F_0 \left( \frac{\epsilon}{\epsilon_m} \right)^{-\Gamma_{\text{syn}}} + \left( \frac{\epsilon}{\epsilon_m} \right)^{-\Gamma_{\text{com}}},$$

(2)

where $\epsilon_m$ is the photon energy at which the fluxes due to synchrotron and SSC processes are equal to $F_0$ and $-\Gamma_{\text{syn}}$ and $\Gamma_{\text{com}}$ are the synchrotron and SSC spectral indices, respectively.

Applying this, we find that the convex X-ray spectra of PKS 2155-304, corresponding to the observation IDs 0158961401, 0411780101 and 0411782021 can be well-fitted with a double power-law function. However, a direct comparison between the fit statistics of the double power-law and the log-parabola functions cannot be done due to the difference in the number of free parameters. The log-parabolic spectrum (eq. 1) is governed by three parameters ($F_p$, $\alpha$ and $\beta$), while the double power-law spectrum is governed by four parameters ($F_0$, $\epsilon_m$, $\Gamma_{\text{syn}}$ and $\Gamma_{\text{com}}$). To progress, we reduce the number of free parameters of the double power-law function to three by fixing $\Gamma_{\text{com}}$ at a value equal to the best fit spectral index of the simultaneous optical/UV spectrum. The rationale behind this being, if the 0.6-10.0 keV SSC spectrum is produced by the same power-law electron distribution responsible for the optical/UV emission also, then in the Thomson scattering regime both spectral indices will be equal. By this approach, the number of free parameters of the double power-law model is made equal to that of
the log-parabola so that, a direct comparison of fit statistics is possible. The results of fit are given in Table 3 and show that a double power-law model can also explain the convex X-ray spectrum as compared to a log-parabola model. The X-ray spectral curvature of PKS 2155-304 has also been studied by Gaur et al. (2017). Their study also indicated the convex nature of the X-ray spectrum corresponding to the observation ID 0411780701. However, the F-test result suggests this curvature to be minimal. In additional to the $\chi^2$ test, we have performed F-test to obtain the statistical significance of log-parabola or double power-law. This analysis is performed for all the observations and the test results are given in Table 2. We also find that the log-parabola spectral fit to the observation ID 0411780701 do not show any significant improvement over the simple power-law. Hence, we have excluded this observation from the rest of the study.

In principle, the spectral slope and the concavity of the double power-law function can be obtained from the first and second derivatives of $\log F_{dp}$ with respect to log $e$, i.e.,

$$\log F'_{dp} = \frac{d(\log F_{dp})}{d(\log e)} = \left( -\Gamma_{syn}^{x_m} - \Gamma_{com}^{x_m} \right) \frac{x_m^{\Gamma_{syn}^{x_m} + \Gamma_{com}^{x_m}}}{1 + \left( 1 + 2 - \alpha - 2\beta \log \left( \frac{e}{\epsilon_m} \right) \right)^{3/2}}.$$  

$$\log F''_{dp} = \frac{d^2(\log F_{dp})}{d(\log e)^2} = \left( \Gamma_{com}^{x_m} + \Gamma_{syn}^{x_m} \right) \frac{x_m^{\Gamma_{com}^{x_m} + \Gamma_{syn}^{x_m}}}{1 + \left( 1 + 2 - \alpha - 2\beta \log \left( \frac{e}{\epsilon_m} \right) \right)^{3/2}} > 0,$$

where $x_m = e/\epsilon_m$. The positive value of the second derivative reaffirms the convex nature of the chosen double power-law function. The curvature $\kappa_{dp}$ of the double power-law function is given by

$$\kappa_{dp} = \frac{\log F'_{dp}}{\log \left( 1 + (\log F'_{dp})^2 \right)^{3/2}} = \left( \Gamma_{com}^{x_m} + \Gamma_{syn}^{x_m} \right) \frac{x_m^{\Gamma_{com}^{x_m} + \Gamma_{syn}^{x_m}}}{\left( \Gamma_{com}^{x_m} + \Gamma_{syn}^{x_m} \right)^2 + \left( \Gamma_{com}^{x_m} - \Gamma_{syn}^{x_m} \right)^2}.$$  

The valley energy $e_v$, corresponding to the minimum flux in the $vF_v$ representation can be obtained by setting equation (3) to zero, yielding

$$e_v = \epsilon_m \frac{\Gamma_{syn}^{x_m}}{\Gamma_{com}^{x_m}}.$$  

From equation (5), $\kappa_{dp}$ for the case $x_m \ll 1$ will be

$$\kappa_{dp}(x_m \ll 1) \approx \frac{\left( \Gamma_{syn}^{x_m} + \Gamma_{com}^{x_m} \right)^2 \Gamma_{com}^{x_m} \Gamma_{syn}^{x_m}}{(1 + 2\beta)^{3/2}}.$$  

Hence in this case, $\kappa_{dp}(x_m \ll 1)$ will decrease with increasing $\Gamma_{syn} + \Gamma_{com}$. As mentioned before, the optical/UV spectral index could be used as an approximation for $\Gamma_{com}$ while for $\Gamma_{syn}$ we used the results from the double power-law fitting. For the observation 0411780701, $\Gamma_{syn}$ was obtained through a simple power-law fit (Table 3). We calculated the X-ray spectral curvature at 1 keV using the log-parabola model instead of double power-law. This is to avoid any possible bias as $\Gamma_{syn}$ was also estimated assuming a double power-law. In case of a log-parabola function, the curvature in $vF_v$ representation can be obtained as

$$\kappa_{dp} = -\frac{2\beta}{\left( 1 + 2 - \alpha - 2\beta \log \left( \frac{e}{\epsilon_m} \right) \right)^{3/2}}.$$  

We then study the dependence of $\kappa_{dp}$ on the sum of optical/UV and X-ray spectral indices. This is done by redefining the log-parabola function in terms of $\kappa_{dp}$ using equation (8) and adding it as a local model in XSPEC. The best fit $\kappa_{dp}$ values are given in column 7 of Table 3. As can be seen, the spectral curvature can be as high as 0.15. Equation (7) suggests that $\log(\kappa_{dp})$ varies linearly with $\Gamma_{syn} + \Gamma_{com}$. In Figure 1, we plot these quantities and the least square fit, considering both the uncertainties (Press et al. 1992), yielding $a = 0.64 \pm 0.14$ and $b = -0.28 \pm 0.12$ with a goodness-of-fit (Q-value) of 0.89. Hence, this result supports our inference that the convex X-ray spectra of PKS 2155-304 is an outcome of the superposition of a synchrotron and a SSC emission component.

In order to explore the minimum photon energy ($\epsilon_{min}$) that could observationally be associated with SSC emission, we modify equation (2) as

$$F_{dp}(e) = F_0 \left( \frac{1}{\epsilon_m^{\Gamma_{syn}^{x_m}}} \right)^{\Gamma_{syn}^{x_m} + \Gamma_{com}^{x_m}} \Theta(\epsilon - \epsilon_{min}).$$  

where $\Theta$ is a Heaviside function. Using equation (9) as a local model in XSPEC, and fixing $F_0$, $\Gamma_{syn}$, and $\Gamma_{com}$ to their best fit values, we then determined an upper limit $\epsilon_{min,c}$ such that $\epsilon_{min} < \epsilon_{min,c}$ did not modify the fit statistics. In Table 4, we provide the 1-$\sigma$ upper limit on the $\epsilon_{min,c}$ and in Figure 2 we show the variation of $y_{red}^2$ with $\epsilon_{min}$. These findings suggest that the IC power-law can be extended down to at least $\approx 0.6$ keV. It is tempting to extend this further down as the XMM-Newton EPIC instrument is sensitive from 0.15 keV. However, we focused only on 0.6-10 keV range, since there can be contamination due to low pulse height events at the low energy end of the PN camera.

### Table 3: Log-parabola spectral fit results (photons cm$^{-2}$ s$^{-1}$ keV$^{-1}$) for the epochs with convex X-ray spectra (pivot energy fixed at 1 keV).

| Obs. ID       | Date of Observation (yyyy.mm.dd) | $\alpha$  | $\beta$  | norm($10^{-3}$) | $y_{red}^2$(dof) |
|--------------|----------------------------------|-----------|----------|-----------------|-----------------|
| 0158961401   | 2006-05-01                       | 2.63 ± 0.01 | -0.10 ± 0.02 | 14.97 ± 0.06   | 1.06(173)       |
| 0411780101   | 2006-11-07                       | 2.58 ± 0.01 | -0.10 ± 0.02 | 19.41 ± 0.06   | 1.01(184)       |
| 0411780201   | 2007-04-22                       | 2.70 ± 0.01 | -0.04 ± 0.01 | 46.32 ± 0.10   | 1.11(246)       |
| 0411780701   | 2012-04-28                       | 2.90 ± 0.01 | -0.02 ± 0.03 | 5.63 ± 0.02    | 1.11(149)       |

1 We fit a straight line of the form $y = a + bx$ to the set of points $(x_i \pm \Delta x_i, y_i \pm \Delta y_i)$. If Q-value > 0.1 the fit is trustable.
While there will be synchrotron (and correspondingly, SSC) emission below the associated $\gamma_{\text{min}}$, approximately rising as $F_\nu \propto \nu^{1/3}$, and the Convex X-ray Spectra of PKS 2155-304 will not much alter the valley energy range. This constraint can be expressed as

$$\gamma_{\text{min}} \lesssim \sqrt{\frac{2\pi m_e c}{\hbar c \delta}} \epsilon_{\text{min,c}}^{1/4}.$$  

(11)

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off $\gamma_{\text{min}}$ of the radiating electron distribution satisfies

$$\frac{\epsilon_{\text{syn,p}}}{\epsilon_{\text{syn,p}}} \lesssim \gamma_{\text{min}} \lesssim \left[ \frac{2\gamma m_p c^2 (1 + \gamma)}{h e B} \left( \frac{\epsilon_{\text{min,c}}}{\epsilon_{\text{min,c}}} \right) \right]^{1/4}.$$  

The above relation implies that with suitable knowledge of $\delta$, $B$ and $\epsilon_{\text{syn,p}}$, we can constrain $\gamma_{\text{min}}$ through $\epsilon_{\text{min,c}}$ obtained from the convex X-ray spectrum. As we show in Sec. 6, the heuristic arguments employed here to infer $\gamma_{\text{min}}$ are supported by results based on full spectral modelling.

### 5.1 Kinetic Jet Power

If we consider a distribution of radiating electrons that is approximated to a power-law described by

$$N(\gamma)d\gamma = K \left( \frac{\gamma}{\gamma_p} \right)^{p-1} d\gamma; \quad \gamma_{\text{min}} < \gamma < \gamma_p,$$  

then, given $p > 1$ and $\gamma_p \gg \gamma_{\text{min}}$, the total electron number density is dominated by the electrons with energy $\gamma_{\text{min}}$ and is given by

$$N_{\text{tot}} \approx \int_{\gamma_{\text{min}}}^{\gamma_p} N(\gamma)d\gamma \approx \frac{K}{p-1} \left( \frac{\gamma_{\text{min}}}{\gamma_p} \right)^{-p+1}.$$  

Under the heavy (e-p) jet approximation, the mass density of the jet is dominated by protons whose number density is assumed to be equal (charge-neutrality) to that of the non-thermal electrons ($N_{\text{tot}}$). The bulk kinetic power of the jet ($P_{\text{j,heavy}}$) is then typically dominated by protons (for $\gamma_{\text{min}} \ll \left( \frac{m_p}{m_e} \right)$), and if we assume them to be cold, the jet kinetic power will be

$$P_{\text{j,heavy}} \approx \pi R^2 \Gamma^2 \beta p U_p c,$$  

where $U_p = N_{\text{tot}} m_p c^2$ is the proton energy density, $R$ is the size of the jet region, $\Gamma$ is the bulk flow Lorentz factor and $\beta p = (1 - \Gamma^{-2})^{1/2}$. Using equations (13), (15) and (16), $P_{\text{j,heavy}}$ is constrained as

$$\left[ \frac{6m_e c^2 (1 + \gamma)}{2\gamma m_p c^2 \epsilon_{\text{min,c}}} \right]^{1/2} \lesssim \xi P_{\text{j,heavy}} \lesssim \delta^2 \left( \frac{\epsilon_{\text{syn,p}}}{\epsilon_{\text{min,c}}} \right)^{1/2},$$  

where

$$\xi = \left( \frac{p-1}{2\pi^2 R^2 K m_p c^2} \right) \gamma_{\text{min}}^{1-p},$$  

and we assumed $\Gamma = \delta$ and $\beta p \approx 1$.

For a light jet, where the energy density is dominated by electrons and positrons, the kinetic power of the jet ($P_{\text{j,light}}$) becomes

$$P_{\text{j,light}} \approx \pi R^2 \Gamma^2 \beta p U_{\text{e,c}} c,$$  

where $U_{\text{e,c}}$ is the lepton energy density given by

$$U_{\text{e,c}} \approx m_e c^2 \int_{\gamma_{\text{min}}}^{\gamma_p} \gamma N(\gamma)d\gamma \approx \frac{K \gamma_p m_e c^2 (\gamma_{\text{min}})^{-p+2}}{p-2} \left( \frac{\gamma_{\text{min}}}{\gamma_p} \right).$$

Using equation (13), $P_{\text{j,light}}$ is constrained by

$$\left[ \frac{6m_e c^2 (1 + \gamma)}{2\gamma m_p c^2 \epsilon_{\text{min,c}}} \right]^{1/2} \lesssim \xi P_{\text{j,light}} \lesssim \delta^2 \left( \frac{\epsilon_{\text{syn,p}}}{\epsilon_{\text{min,c}}} \right)^{1/2},$$  

where

$$\xi = \left( \frac{p-2}{2\pi R^2 K m_e c^2} \right) \gamma_{\text{min}}^{1-p}.$$  

### 6 BROADBAND SPECTRAL MODELLING

As noted above, estimation of the minimum available energy $\gamma_{\text{min}}$ and the jet power demands knowledge of the source parameters, $\delta$ and $B$. In order to obtain these information, we performed a broadband spectral fitting of the SED considering both synchrotron and SSC emission processes (Sahayananthan et al. 2018). The emission from the source is imitated by assuming the emission region to be a spherical region of size $R$, permeated by a tangled magnetic field $B$ and populated by a broken power-law distribution of the form

$$N(\gamma) = K \left\{ \begin{array}{ll} \left( \frac{\gamma}{\gamma_p} \right)^{-p} & \gamma_{\text{min}} < \gamma < \gamma_p \\ \left( \frac{\gamma}{\gamma_{\text{max}}} \right)^{-q} & \gamma_p < \gamma < \gamma_{\text{max}} \end{array} \right\}$$

The Doppler factor $\delta$ determines the flux enhancement due to the relativistic motion of the emission region along the jet. The observed flux due to synchrotron and SSC emission processes, after
accounting for the relativistic and cosmological effects will be (e.g., Begelman et al. 1984; Dermer 1995)

\[ F_{\text{obs}}(\varepsilon) = \frac{\delta^3 (1+z)}{d_L^2} V \left[ j_{\text{syn}} \left( \frac{1+z}{\delta_D} \varepsilon \right) + j_{\text{SSC}} \left( \frac{1+z}{\delta_D} \varepsilon \right) \right] \]  

(24)

where, \( j_{\text{syn}} \) and \( j_{\text{SSC}} \) are the synchrotron and SSC emissivities measured in the frame of emission region (e.g., Sahayanathan et al. 2018; Finke et al. 2008), \( d_L \) is the luminosity distance and \( V \) is the volume of the emission region. For the SSC emissivity, we have considered the full Klein-Nishina cross section for the scattering process. The spectrum is then essentially governed by seven source parameters namely, \( p, q, K, \gamma_p, R, B \) and \( \delta \). The limited information available from the optical and X-ray energies does not allow us to constrain all these parameters and hence, we impose certain conditions to determine the characteristic range of the source parameters. We assume equipartition between the emitting electron energy density and the magnetic field. This assures a minimum energy budget (Burbidge 1959) and using equation (19) we can express \( B \) as

\[ B \approx \sqrt{\frac{8\pi q K \gamma_p c^2}{(p-2)}} \left( \gamma_{\text{min}} \right)^{-p/2} \]  

(25)

where \( \eta = 1 \) corresponds to equipartition and \( \gamma_{\text{min}} \) can be constrained from equation (13). The parameter \( \gamma_p \) determines the SED peak of the synchrotron spectral component

\[ \epsilon_{\text{syn},p} = \left( \frac{\hbar}{1+z} \right) \left( \frac{eB}{2\pi mc^3} \right) \gamma_p^2 \]  

(26)

and \( \epsilon_{\text{syn},p} \) can be obtained from the intersection of extrapolated optical/UV and X-ray spectra. Finally, we constrain \( R \) by assuming a variability timescale, \( t_{\text{var}} \), as

\[ R \approx \frac{c}{1+z} 5t_{\text{var}} \]  

(27)

Along with these constraints, we also included archival \( \gamma \)-ray data of the source as obtained by Fermi-LAT for the spectral fit. Since simultaneous \( \gamma \)-ray observations were not available, we chose observations in 2008 (Aharonian et al. 2009) as this being the closest one available with the X-ray observation epochs (2006-2007) considered in this work. In addition, we also included 2013 \( \gamma \)-ray observations (Madejski et al. 2016) during which the source was found to be in its lowest flux state.

We developed a numerical code to generate the synchrotron and SSC emission spectra from the source parameters, along with the constraints discussed above. The computer routine is added as a local model in XSPEC and used to fit the optical/UV, X-ray and the archival \( \gamma \)-ray observations (Sahayanathan et al. 2018). The fitting procedure is performed as follows: We first fixed \( t_{\text{var}} = 1 \) day, \( \eta = 1 \) and \( \epsilon_{\text{min},c} \) to values obtained from Table 4. Following this, the best fit parameters were obtained by allowing the parameters \( p, q \) and \( \epsilon_{\text{syn},p} \) to vary within the confidence intervals obtained from the power-law/broken power-law/double power-law spectral fits to optical/UV, X-ray and \( \gamma \)-ray spectra; whereas, \( \delta \) and \( B \) were set to vary freely. Next freezing the parameters to their best fit values except for \( \delta \) and \( B \), we obtained the confidence intervals on these two parameters. In order to obtain error in the parameters, XSPEC demands \( \chi^2_{\text{red}} < 2 \). To achieve this we added 2 per cent additional error (systematic error in XSPEC) for the epochs corresponding to observation IDs 0158961401 and 0411780101, and 7 per cent additional error for 0411780201. The best fit source parameters corresponding to the two archival \( \gamma \)-ray observations are given in Table 5 and 6. Using the best fit parameters, we obtained the range of \( \gamma_{\text{min}}, P_{\text{jet,heavy}} \) and \( P_{\text{jet,light}} \) which are also provided in Table 5 and 6 (bottom). In the left panel of Figure 3, we show the best fit broadband SED along with the observed fluxes and in right panel, the XSPEC fit results with the residuals corresponding to 2008 \( \gamma \)-ray observation. We note that the spectral fit is very sensitive to the choice of \( \epsilon_{\text{min},c} \) or its equivalent \( \gamma_{\text{min}} \). In Figure 4, we show the variation of \( \chi^2 \) with \( \gamma_{\text{min}} \) while the rest of source parameters are fixed to their best-fit values for the spectral fit corresponding to the XMM-Newton observation ID 0158961401. For the best fit parameters given in Table 5, the minimum \( \chi^2 \) is achieved when \( \gamma_{\text{min}} \approx 330 \). The required kinetic jet power for a light jet is of the order 3 \( \times 10^{34} \) erg s\(^{-1}\), and nearly an order of magnitude higher for a heavy jet. Assuming a black hole mass of \( \sim 5 \times 10^8 \) \( M_\odot \), this would roughly correspond to levels of \( \sim 0.1 \) per cent and \( \sim 1 \) per cent of the maximum possible jet power, respectively (e.g., Katsoulakos & Rieger 2018).
Table 5. The best fit source parameters and inferred quantities of PKS 2155-304 for the three observation IDs as obtained using a synchrotron and SSC emission model. The gamma-ray reference data are from 2008 Fermi-LAT observations (Aharonian et al. 2009). $\delta$: Doppler factor, B: magnetic field (Gauss), $p$ and $q$: low and high energy particle spectral indices, $\epsilon_{\text{min,c}}$: observed minimum photon energy of the Compton component (keV) (fixed to the values obtained from Table 4), $\epsilon_{\text{syn,p}}$: synchrotron peak energy (keV), $\gamma_{\text{min}}$: minimum electron energy (in units of $mc^2$), $P_{\text{jet,heavy}}$: jet kinetic power (log) estimated for an e-p jet (erg s$^{-1}$), $P_{\text{jet,light}}$: jet kinetic power (log) estimated for a light jet (erg s$^{-1}$). Fixed parameters are $q = 1$, $t_{\text{var}} = 1$ day and $\gamma_{\text{max}} = 10^7$.

| Parameters | (0158961401) | (0411780101) | (0411780201) |
|------------|--------------|--------------|--------------|
| $\delta$   | 21.19$^{+0.71}_{-0.66}$ | 23.94$^{+0.10}_{-0.08}$ | 31.37$^{+1.31}_{-1.16}$ |
| B          | 0.238$^{+0.013}_{-0.009}$ | 0.209$^{+0.010}_{-0.008}$ | 0.114$^{+0.010}_{-0.008}$ |
| $p$        | 2.70         | 2.73         | 2.43         |
| $q$        | 4.36         | 4.36         | 4.36         |
| $\epsilon_{\text{min,c}}$ | 0.607 | 0.619 | 0.654 |
| $\epsilon_{\text{syn,p}}$ (10$^{-2}$) | 3.31 | 3.64 | 5.02 |

Properties

| $\gamma_{\text{min}}$ | 59.40 - 328.33 | 67.27 - 330.45 | 60.61 - 364.66 |
|-----------------------|----------------|----------------|----------------|
| $P_{\text{jet,heavy}}$ | 45.40 - 44.74 | 45.55 - 44.84 | 45.52 - 44.63 |
| $P_{\text{jet,light}}$ | 44.41 - 44.36 | 44.56 - 44.46 | 44.56 - 44.40 |

Table 6. Same as in Table 5, but for gamma-ray reference data based on 2013 Fermi-LAT observations (Madejski et al. 2016).

| Parameters | (0158961401) | (0411780101) | (0411780201) |
|------------|--------------|--------------|--------------|
| $\delta$   | 24.56 $^{+0.04}_{-0.04}$ | 26.10 $^{+0.08}_{-0.08}$ | 39.62 $^{+0.06}_{-0.06}$ |
| B          | 0.1904 $^{+0.0005}_{-0.0005}$ | 0.187 $^{+0.001}_{-0.001}$ | 0.0742 $^{+0.0002}_{-0.0002}$ |
| $p$        | 2.78         | 2.80         | 2.43         |
| $q$        | 4.36         | 4.36         | 4.36         |
| $\epsilon_{\text{min,c}}$ | 0.607 | 0.619 | 0.654 |
| $\epsilon_{\text{syn,p}}$ (10$^{-2}$) | 3.70 | 3.81 | 5.03 |

Properties

| $\gamma_{\text{min}}$ | 77.70 - 334.44 | 92.17 - 332.36 | 60.55 - 382.64 |
|-----------------------|----------------|----------------|----------------|
| $P_{\text{jet,heavy}}$ | 45.44 - 44.82 | 45.50 - 44.92 | 45.59 - 44.65 |
| $P_{\text{jet,light}}$ | 44.50 - 44.43 | 44.60 - 44.52 | 44.61 - 44.44 |

7 DISCUSSION AND CONCLUSION

Our analysis shows that the convex X-ray spectra of PKS 2155-304 can be successfully interpreted as a combination of synchrotron and SSC spectral components. We demonstrate that this result along with the knowledge of source parameters can be effectively utilized to draw better constraints on the minimum energy $\gamma_{\text{min}}$ of the emitting electron distribution and the power of the blazar jet. In general, the hard X-ray emission of PKS 2155-304 is expected to reveal a convex nature irrespective of flux state. NuSTAR observation of the source at 3-79 keV can thus effectively probe the valley regime and provide further constraints on $\gamma_{\text{min}}$. In the current work, however, we wanted to highlight the occasional convex spectra that have been observed in the soft X-ray regime using XMM-Newton observations. The constraints on $\gamma_{\text{min}}$ are derived from these epochs of convex soft X-ray spectra. The source parameters were obtained through statistical fitting of the broadband SED using synchrotron and SSC emission processes. We observed that the spectral fit is very sensitive to the parameter $\gamma_{\text{min}}$. To explore in detail how the jet power depends on $\gamma_{\text{min}}$, we replaced the parameter $\epsilon_{\text{min,c}}$ with $\gamma_{\text{min}}$ in our numerical emission model and repeated the fitting procedure (as mentioned in §6). In Figure 5, we show the variations of $P_{\text{jet,heavy}}$ (solid purple line) and $P_{\text{jet,light}}$ (dashed magenta line) with respect to $\gamma_{\text{min}}$ along with the goodness-of-fit $\chi^2$ in the bottom (solid red line). The fitting was performed on the SED corresponding to the XMM-Newton observation ID 0158961401 along with its 2008 $\gamma$-ray reference spectrum. The horizontal red dashed line corresponds to $\chi^2 = 1$ and the vertical blue dashed lines corresponds to the limiting values of $\gamma_{\text{min}}$ (Table 5). The dependence of $\chi^2$ over $\gamma_{\text{min}}$ shown in Figure 4 satisfies the condition obtained earlier in §§ equation (13). We found that $P_{\text{jet,heavy}}$ varies more strongly with $\gamma_{\text{min}}$ than $P_{\text{jet,light}}$. Also, as $\gamma_{\text{min}}$ approaches $\gamma_{\text{max}}$, the allowed range of jet power can be constrained by the gray-shaded area in figure 5.

In general, the non-availability of simultaneous $\gamma$-ray data introduces some uncertainty on the fit parameters. On the other hand, Table 5 and 6 reveal that the estimates for $\gamma_{\text{min}}$ and the jet kinetic power do not vary much for the two different gamma-ray flux states of the source. The obtained limits on $\gamma_{\text{min}}$ and jet powers may therefore be viewed as typical values for PKS 2155-304. In principle, uncertainty in the size of the emission region $R$ could also impact these estimates. To test this, we repeated the fitting by freezing $t_{\text{var}}$ to a predefined value while setting $q = 1$ and $\gamma_{\text{min}} = 328.33$. Figure 6 shows the variation in $P_{\text{jet,light}}$ and $P_{\text{jet,heavy}}$ along with the $\chi^2$ (bottom panel). The variation in jet power is found to be within the same order while $t_{\text{var}}$ changes from 0.1 to 2 days. This suggests that our inferred values represent the typical parameter space of the source.
The best fit SEDs corresponding to three epochs with convex X-ray spectrum and the Fermi-LAT reference observations of the source during 2008 and 2013. The solid line represents synchrotron and the dashed line represents SSC contribution. The thick gray band represents the combined emission with the width of the band representing the systematic error added to the model. The XSPEC spectral fit, along with residual are given in the right panel corresponding to the 2008 gamma-ray observations.

The assumption of equipartition between the particle energy density and magnetic field relies on the principle that the source remains in its minimum energy state. However, there is no consensus that this condition should be satisfied rigorously. For instance, the chosen equipartition condition assumes that the radiating particle distribution largely determines the total electron density. However, protons may also carry significant energy (while still being radiatively inefficient) and for such conditions $\eta \neq 1$. Similarly, when the electrons undergo non-radiative losses (e.g., adiabatic expansion) along with synchrotron losses, the equipartition condition may not be satisfied (Lefa et al. 2011). Besides this, broadband spectral fitting of blazar SED by synchrotron and IC emission also indicates significant deviation from equipartition (e.g., Tavecchio & Ghisellini 2016). To study the dependence of jet power on the assumed equipartition, we also repeated fitting for different values of $\eta$ keeping $\gamma_{\text{var}} = 1$ and $\gamma_{\text{min}} = 328.33$. We found that the jet power varies by a factor of 10 as $\eta$ varies from 0.1 to 10. This large variation advocates $\eta$ to be an important parameter in deciding the energetics of the source.

It is widely accepted that the broadband non-thermal emission from blazars originates from relativistic jets. The formation and collimation of these jets, however, still remains an unresolved puzz-
Blandford & Znajek (1977) indicate a thermal coupling that is some-
what stronger (ζ ~ 0.2 – 0.5), variations in magnetization, shock speed and orientation may possibly explain the difference. If confirmed, this would tend to favour an e-p composition, at least for the X-ray emitting part of the jet.

Our results show that the convex X-ray spectra of blazars offer important insights into the source energetics as well as the matter content of jets. As indicated above, a crucial uncertainty in the present work relates to the equipartition parameter η. An appropriate value of η could be obtained through a detailed study of the particle acceleration process. For instance, if the particles are energized through shock acceleration then a fraction of the shock energy is spent in enhancing the magnetic field. A clear understanding about the energy budget involved demands detailed numerical simulation of relativistic MHD jet flow. This should be further supplemented with detailed spectral and temporal behaviour which can provide inputs/tests for the simulations. One such information can be the simultaneous broadband SED extending up to GeV/TeV gamma-ray energies during lower flux states, supplemented with the temporal behavior of the source. Future upcoming ground-based Cherenkov Telescope Array observations will have the capability to gather information from the source at VHE energies, even at low flux states. This along with the inputs from other wavebands could play an important role in providing valuable information regarding the source energetics.

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Figure 5. Variation in jet power as a function of minimum electron energy \(\gamma_{\text{min}}\) (expressed in units of \(m_e c^2\)) for the observation ID 0158961401. The solid purple line corresponds to \(P_{\text{jet,heavy}}\) and the dashed magenta line corresponds to \(P_{\text{jet,light}}\). The red solid line in the bottom panel is the best fit \(\chi^2\) for different \(\gamma_{\text{min}}\) values and the dashed line denotes \(\chi^2_{\text{red}} = 1\). The vertical blue dashed lines represent the limiting values of \(\gamma_{\text{min}}\). The gray shaded area is the allowed ranges of jet kinetic power.

Figure 6. Variation in jet power for a range of variability time-scale \(t_{\text{var}}\) (in days) corresponding to the observation ID 0158961401. The solid purple line corresponds to \(P_{\text{jet,heavy}}\) and the dashed magenta line corresponds to \(P_{\text{jet,light}}\). The red solid line in the bottom panel is the best fit \(\chi^2\) for different \(\gamma_{\text{min}}\) values and the dashed line denotes \(\chi^2_{\text{red}} = 1\). The vertical blue dashed line represents \(t_{\text{var}} = 1\) day.

DATA AVAILABILITY

The data underlying this article are publicly available from the HEASARC\(^3\) and the Fermi-LAT\(^4\) archives.

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\(^3\) https://heasarc.gsfc.nasa.gov/
\(^4\) https://fermi.gsfc.nasa.gov/ssc/data/access/

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Figure 7. Variation in jet power as a function of the equipartition parameter $\eta$ corresponding to the observation ID 0158961401. The solid purple line corresponds to $P_{\text{jet,heavy}}$ and the dashed magenta line corresponds to $P_{\text{jet,light}}$. The red solid line in the bottom panel is the best fit $\chi^2$ for different $\eta$ values and the dashed line denotes $\chi^2_{\text{red}} = 1$. The vertical blue dashed line represents $\eta = 1$.