The Hard X-Ray Emission of the Blazar PKS 2155–304

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Abstract

The synchrotron peak of the X-ray bright High Energy Peaked Blazar PKS 2155–304 occurs in the UV-EUV region and hence its X-ray emission (0.6–10 keV) lies mostly in the falling part of the synchrotron hump. We aim to study the X-ray emission of PKS 2155–304 during different intensity states in 2009–2014 using the XMM-Newton satellite. We studied the spectral curvature of all of the observations to provide crucial information on the energy distribution of the nonthermal particles. Most of the observations show curvature or deviation from a single power law and can be well modeled by a log parabola model. In some of the observations, we find spectral flattening after 6 keV. In order to find the possible origin of the X-ray excess, we built the Multiband Spectral Energy distribution. We find that the X-ray excess in PKS 2155–304 is difficult to fit in the one zone model but, could be easily reconciled in the spine/layer jet structure. The hard X-ray excess can be explained by the inverse Comptonization of the synchrotron photons (from the layer) by the spine electrons.

Key words: BL Lacertae objects: general – BL Lacertae objects: individual (PKS 2155–304) – galaxies: active

1. Introduction

Blazars are multiwavelength, multi-timescale phenomena (Ulrich et al. 1997) and their extreme properties are thought to be due to relativistic jets pointing nearly to our line of sight (≤10°) (e.g., Urry & Padovani 1995). Blazar light curves show an erratic and unpredictable behavior in terms of flare strength and duration from event to event.

The broadband (from IR to TeV energies) spectral energy distribution (SED) of blazars are characterized by a broad double peaked structure. The peak of the low-energy spectral component is found at X-ray/UV energies for high energy peaked blazars (HBLs) and at optical energies for low-energy peaked blazars (LBLs). The peak of the high energy spectral component for HBLs occurs at GeV/TeV energies while for LBLs it is usually at MeV/GeV energies. In fact, the peak of the first spectral component is known to inversely correlate with the luminosity of the blazar and different kinds of blazars can be classified based on their peak energy to form a sequence referred to as the blazar sequence (Fossati et al. 1998; Ghisellini et al. 1998; Giommi et al. 2012).

Phenomenologically the SED of TeV blazars can be roughly explained by invoking nonthermal electrons, which are approximately distributed in energy in a broken power-law shape (Fossati et al. 2000; Saugé & Henri et al. 2006). The low-energy spectral component of the SED arises from the synchrotron emission of these particles. The high energy component is then modeled as synchrotron self-Compton and/or external photon inverse Comptonization by the same nonthermal distribution. The nonthermal particles are believed to be produced in a so-called “acceleration” region, where the balance of the acceleration and escape timescales produces a single power-law distribution. These electrons escape into a larger “cooling” region, where they produce the observed synchrotron and inverse Compton components (Kirk et al. 1998). Since the radiative cooling rate of these processes is proportional to the energy square of the electrons, the high energy electrons are affected by the cooling, while the low-energy ones are not. This differentiates the electron population into two regimes and it is believed that the two power-law forms of the empirical broken power-law correspond to these two regimes (Kardashev 1962; Pacholczyk 1970). While this interpretation is popular and standard, it should be noted that theoretically the spectral index difference between the two power laws predicted from such a radiative cooling model should be ~0.5 which is not often observed (Sikora et al. 2009 and references therein).

A simple description of the X-ray data of blazars is the log parabola model. Here the power-law index is not a constant but varies slowly with energy, i.e., ∝log E and hence the name log parabola. This model has often been invoked to fit the entire SED of blazars (Landau et al. 1986; Massaro et al. 2004; Chen 2014) and such curved spectra of blazars are known to arise by synchrotron or inverse Compton radiation from electron distributions featuring in log parabola shape (Tramacere et al. 2007; Paggi et al. 2009). There is a correlation observed between the curvature parameter of the log parabola model β and the energy at which the component peaks (Massaro et al. 2004, 2008, 2011; Tramacere et al. 2007; 2009), which is consistent with the theoretical expectations (Tramacere et al. 2007; Paggi et al. 2009). However, it is unlikely that a single log parabola model is the true representative of the complete SED data and indeed for several optical–X-ray SED fits it is found to be inadequate, requiring additional components (e.g., Bhagwan et al. 2014). Massaro et al. (2004) and PKS 2155–304 is the brightest X-ray BL Lac (Griffiths et al. 1979; Schwartz et al. 1979; Brinkmann et al. 1994; Giommi et al. 1998) and is a confirmed TeV γ-ray source by the observations of the H.E.S.S. collaboration in 2002 and 2003 (Aharonian et al. 2005). The synchrotron hump peaks in
the UV/EUV and is <100 eV even in the very high states (Zhang 2002; Massaro et al. 2008). The brightness of the source and that it has been observed several times by X-ray satellites makes it an excellent source to study its spectral curvature. It has been an important target of various X-ray satellites like ASCA, BeppoSAX, EGRET, RXTE, HESS, Swift XRT, and XMM-Newton (Sreekumar & Vestrand 1997; Vestrand & Sreekumar 1999; Tanihata et al. 2001; Zhang 2002; Massaro et al. 2004; Aharonian et al. 2005; Zhang et al. 2005; Foschini et al. 2007; H.E.S.S. Collaboration et al. 2014; Kapanadze et al. 2014). Depending on various flux states, several works have reported curvature in the X-ray band (Fossati et al. 2000; Foschini et al. 2007; Massaro et al. 2008; Chen 2014 and references therein). On several occasions, the γ-ray luminosity of PKS 2155–304 dominates over the low-energy synchrotron component, a trend similar to flat spectrum radio quasars (e.g., Zhang 2008; Aharonian et al. 2009; Massaro et al. 2011).

The large effective area and high spectral resolution of XMM-Newton has provided unprecedented X-ray spectral information for PKS 2155–304. XMM-Newton has been observing the source frequently since 2000. In a sample study of several blazars, Massaro et al. (2008) analyzed a number of XMM-Newton observations of PKS 2155–304 before 2007 and fit all of them using the log parabolic model. They found that the curvature versus peak energy correlation was similar to other blazars while the curvature versus peak luminosity was not. On the other hand, Zhang (2008) reported spectral hardening (i.e., negative curvature) for two observations in 2006. The spectral curvature is very small (i.e., −0.05 to −0.09) and interpreted it as the detection of the Inverse Compton component in the X-ray band. However, most observations of the source show regular positive curvature and the above two observations may be taken as special cases when the inverse component was revealed. Bhargava et al. (2014) analyzed 20 XMM-Newton observations of PKS 2155–304 during the period of 2000–2012 and model the simultaneous Optical/UV–X-ray SED using the log-parabolic model. Four observations from 2009–2012, which we are analyzing in this work, are presented by them. They found that the log-parabolic model is not adequate and requires an additional power-law component to model the simultaneous Optical/UV–X-ray SED. Recently, using NuSTAR observations, Madejski et al. (2016) found significant hard X-ray excess for PKS 2155–304 during epoch 2013 and modeled the Multiband SED with the one zone model.

Here, our motivation is to study the X-ray spectral curvature of PKS 2155–304 during the period of 2009–2014 using the XMM-Newton observations. We study the X-ray spectra of PKS 2155–304 during various flux states and tested if they are well described with a single power law or curved log parabola model. In some of the observations, we found concave X-ray spectra/X-ray excess. In order to find the possible physical origin of concave X-ray spectra, we construct the simultaneous Multiwavelength SEDs of PKS 2155–304 and determine various parameters of the blazar jet.

The paper is structured as follows. In Section 2, we give a brief description of the observations and the data reduction method. The results of the analysis are presented in Section 3, which are discussed and concluded in Section 4.
2.2. Optical/UV Data

The Optical/UV Monitor Telescope (OM hereafter) on board XMM-Newton provides the facility to observe a source simultaneously in optical and UV bands along with the X-ray bands, with a very high imaging sensitivity (Mason et al. 2001). The OM can collect data with time resolution of 0.5 s for the wavelength range of 170–650 nm with six broadband filters, three in the optical and three in the UV, with an FOV covering 17 arcmin of the central region of the X-ray telescope FOV. The optical U, B, and V filters collect data in the wavelength ranges of 300–390 and 390–490, 510–580 nm, respectively, and the ultraviolet UV W2, UV M2, and UV W1 filters collect data in the wavelength ranges of 180–225, 205–245, and 245–320 nm, respectively. PKS 2155–304 was observed with OM in imaging mode in all of the filters during these observations. We reprocess the OM imaging data using the standard omichain pipeline of SAS, from which we get a combolist file containing the calibrated data with their errors for all the sources that are present in the field of view. The counts, instrumental magnitude, and the fluxes for PKS 2155–304 are extracted from the file and are provided in Table 2.

3. Results

3.1. Temporal Variability

The XMM-Newton optical/UV/X-ray light curves of PKS 2155–304 are presented in Figure 2. Each observational point in the figure indicates the average count rate in the X-ray (0.6–10 keV) band and OM filters. It can be seen that the source is variable in all of the bands during 2009–2014. The fractional variability amplitudes corresponding to the X-ray, UVW1, UVM2, UVW2, U, B, and V bands are 55.12 ± 1.13, 43.33 ± 0.09, 42.87 ± 0.19, 42.18 ± 0.27, 45.01 ± 0.12, 43.18 ± 0.12, and 40.41 ± 0.21, respectively. The variability amplitudes at optical and UV frequencies are smaller than that observed at X-ray frequencies and is consistent with the previous findings (Zhang et al. 2006; Osterman et al. 2007). The correlation between X-ray versus optical/UV and optical versus UV is shown in Figure 3. It can be seen that optical and UV emission are significantly correlated (Pearson correlation coefficient, \( r = 0.99, \rho = 5.96 \times 10^{-6} \)), whereas there is weak correlation between X-ray w.r.t optical/UV (Spearman correlation coefficient, \( \rho = 0.89, p = 0.02 \)).

During all six observation epochs, X-ray variability is clearly detected with recurrent flare-like events.

3.2. Spectral Variability

The XSPEC software package version 12.8.1 is used for spectral fitting. The Galactic absorption \( n_H \) was fixed to \( 1.52 \times 10^{20} \text{cm}^{-2} \) (Lockman & Savage 1995) and the Xspec routine “cflux” was used to obtain unabsorbed flux and its error. The spectra are fitted with a simple power law defined as \( kE^\Gamma \), a broken power law, which is defined as \( kE^{\Gamma_1} \) for \( E < E_{\text{break}} \), \( kE^{\Gamma_2} \) otherwise, and a log parabolic model. In the log parabolic model, the spectrum is assumed to be \( \propto E^{-\Gamma(E)} \), where the photon index \( \Gamma \) is not a constant but varies logarithmically with energy, i.e.,

\[
\Gamma(E) = \alpha + \beta \log(E/E_1). \tag{1}
\]

Here, \( \alpha \) is a parameter denoting the local spectral index at \( E_1 \) and \( \beta \) is the curvature parameter. Together with the normalization, \( \alpha \) and \( \beta \) are the three parameters of the spectrum. Without loss of generality, \( E_1 \) is fixed to some convenient value, which in our case is the lowest energy of the spectra \( E_1 = 0.6 \) keV. The spectral parameters of all the models are presented in Table 3. In most of the observations, log parabolic models give better descriptions by giving systematically lower \( \chi^2 \) values which can be seen by the \( F \)-values in Table 3. The spectral fitting for all of the observations is shown in Figure 4.
In 2012 pointing, it can be seen that the residuals around 6 keV show deviations in the upward direction. The spectrum shows a break at around $E_p \sim 6.3$ keV, indicating the flattening in the spectrum. The log parabolic model also shows a mild negative curvature of $-0.07$. It can be noted that this pointing has the lowest flux among all of the observations. From the spectral fitting of other observations, it can be seen that there are positive residuals around 7 keV. Although, the fitting parameters do not show any negative curvature for these observations. The spectral flattening/negative curvature could be attributed to the weak contamination of the IC component in the synchrotron component as reported in previous studies (e.g., Zhang 2008; Madejski et al. 2016). In order to further search for the physical origin of these positive residuals, we construct the multiwavelength spectra of these six epochs.
3.3. Multiwavelength Spectral Energy Distribution

As discussed above, *XMM-Newton* observation of PKS 2155–304 during 2012 shows significant concave X-ray spectra. Fortunately, the *Nuclear Spectroscopic Telescope Array (NuSTAR)* satellite has a simultaneous observation of PKS 2155–304 in 2013 with our observations of *XMM-Newton*. This data of PKS 2155–304 has been successfully reduced by Madejski et al. (2016) and they found significant X-ray spectral flattening during epoch 2013. Hence, we also included the *NuSTAR* data of this epoch in our SED fitting. To explore the origin of such a concave feature, we construct simultaneous broadband SEDs from radio through $\gamma$-ray for our observations from epochs 2009 to 2014. *Fermi/LAT* $\gamma$-ray data and radio data reductions are provided below in Sections 3.3.1 and 3.3.2, respectively. PKS 2155–304 is a TeV $\gamma$-ray source, which is detected by the H.E.S.S. collaboration (Aharonian et al. 2005). Unfortunately, we do not have simultaneous TeV data corresponding to our observations. Hence, we collect the historical TeV spectra from the H.E.S.S. Collaboration et al. (2012) just to guide the broadband SEDs. The TeV photons can be absorbed by extragalactic background light (EBL) through the pair production effect. Therefore, we correct the observed TeV spectra by employing the EBL model of Franceschini et al. (2008). For the epoch 2013, we collect the hard X-ray data from Madejski et al. (2016; mainly detected by *NuSTAR*) to make the concave X-ray spectra more clear. Finally, out of six simultaneous broadband SEDs (except TeV band), two X-ray spectra have shown concave features, i.e., during epochs 2012 and 2013. All six of these broadband SEDs are presented in Figure 5.

### 3.3.1. $\gamma$-Ray Data

The Fermi Large Area Telescope (LAT) is a gamma-ray imaging telescope, continuously scanning the whole sky every ~3 hours for photons with energies >20 MeV (Atwood et al. 2009). The data used here for generating the gamma-ray SEDs are of 1-month duration centered on the corresponding *XMM* observations and were analyzed following the standard procedure for the PASS 8 instrument response function. The 100 MeV–300 GeV energy bin was divided into multiple bins and in each, only photon-like events classified with keywords EVCLASS = 128 and EVTYPE = 3 were selected from a 15° circular region centered on the source position. The gamma-ray events from the Earth’s limb were minimized by restricting the events to a maximum zenith angle of 90°. These events were then further filtered with the instrument good time intervals using the standard cut “((DATA_QUAL > 0) && LAT_CONFIG == 1)” The resulting events were then modeled using the maximum likelihood method with an input model provided file and associated exposure map calculated on ROI and additional 10° around it. The source model file was generated from the 3rd *Fermi*-LAT catalog (3FGLgll_psc_v16.fit; Agero et al. 2015) including the Galactic (gll_iem_v06.fits) and extragalactic (iso_P8R2_SOURCE_V6_v06.txt) contribution through the respective template provided by the LAT team.

For each energy bin, the fitting was performed iteratively, removing insignificant sources with Test Statistics <10 following Kushwaha et al. (2014) until it converged. For PKS 2155–304, we used a power-law model. The best-fit value was finally used to derive the energy flux to construct the gamma-ray SED.

### 3.3.2. Radio Data

Radio observations at 22.2 GHz are carried out with the 22 m radio telescope (RT-22) at the Cromane Astronomical Observatory (CrAO). Observations at 37.0 GHz are made with the 14 m radio telescope of Aalto University’s Metsahovi Radio Observatory in Finland. For our measurements, we used
Figure 4. Spectral fitting of six observations of PKS 2155–304 in 0.6–10 KeV. Each spectra is fitted using the power-law, broken power-law, and log parabolic models and the data-to-model ratio is shown in the three subpanels for each spectra in red, black, and blue colors, respectively.
two similar Dicke switched radiometers of 22.2 and 36.8 GHz. More details about the observations and data reduction are provided in Gaur et al. (2015).

3.3.3. One Zone Model

The multiwavelength emission of HSP BL Lacs often show correlated variability and therefore are thought to be produced from a single emitting region, except the radio emission, which is probably the superimposed emissions of many optically thick emitting regions along the jet (e.g., Blandford & Königl 1979; Ghisellini et al. 1985). One zone synchrotron + synchrotron self-Compton (SSC) model is successful in explaining the multiwavelength SED of HSP BL Lacs (except radio band). Therefore, we adopt the one zone model to fit the SEDs of PKS 2155–304, and the concave X-ray spectra is thought to the composite spectra of synchrotron and SSC emissions produced from the same electron population as also reported by Zhang (2008) and Madejski et al. (2016). Since we are interested in those SEDs that have concave X-ray spectra, in this work, we only model two SEDs of epochs 2012 and 2013. We briefly describe the model here. For detailed information, please see Chen (2017). The model assumes a homogeneous and isotropic emission region, which is a sphere with radius $R$ that has a uniform magnetic field with strength $B$ and a uniform electron energy distribution as described by

$$N(\gamma) = \begin{cases} 1 \gamma^{-p} \\ N_0 \gamma^{-p} \left( \frac{\gamma_0}{\gamma} \right)^3 10^{-b \log^3 (\gamma/\gamma_0)} \end{cases} \begin{array}{c} \gamma_{\text{min}} \leq \gamma < \gamma_0 \\ \gamma_0 < \gamma \leq \gamma_{\text{max}} \end{array}$$

The emission region moves relativistically with a Lorentz factor $\Gamma = \sqrt{1 - \beta^2}$ and a viewing angle $\theta$, which forms the Doppler beaming factor $\delta = 1/|\Gamma(1 - \beta \cos \theta)|$. Frequency and luminosity can be transformed from the jet frame to AGN frame as $\nu = \delta \nu'$ and $\nu L(\nu) = \delta^2 \nu' L'(\nu')$, respectively. The prime refers to the values in the jet frame. Due to causality argument, the variability timescale set a constraint on the size of the emission region $R < \delta \Delta t / (1 + \varepsilon)$. Because the epochs 2012 and 2013 are quiet states, therefore for simplicity, variability timescale is set to be $\Delta t = 10 \text{ days}$ during our SED modeling. All jet parameters, except $R$ are constrained through SED modeling. The Klein–Nishina (KN) and SSA effects are also considered (see Chen 2017).

Recently, Kataoka & Stawarz (2016) presented the NuSTAR observations of Mrk 421 and found X-ray spectra to be concave (hard X-ray excess) in its low state. They explained this feature to be the power-law extension of Fermi/LAT spectra. However, Chen (2017) explored the possibility of whether the hard X-ray excess of Mrk 421 is produced from the inverse Compton emission of the low-energy end of the power-law electron distribution. It is found that the hard X-ray excess of Mrk 421 could be well fitted by the one zone model provided the minimum electron energy would be $\gamma_{\text{min}} \approx 19$. However, it is found that the predicted radio flux was significantly larger than the observed radio flux, even after considering synchrotron self-absorption effects (Chen 2017). Due to the over-prediction of the radio flux, it is implied that the observed hard X-ray excess of Mrk 421 could not be the low-energy tail of the Fermi/LAT $\gamma$-ray spectra.

Similarly, for PKS 2155–304, first we model the broadband SED (eyeball fit) for epochs 2012 and 2013 having hard X-ray excess using the one zone model. We find that in order to fit these two concave X-ray spectra within the one zone model, the minimum electron energy required should be at least $\gamma_{\text{min}} \approx 30$. The modeled curves are shown in Figure 6, where we presented three SEDs with $\gamma_{\text{min}} = 10, 30, \text{and } 100$, respectively. The corresponding fitting parameters for these $\gamma_{\text{min}}$ are provided in Table 4. It can be seen from the figure that due to the cutoff of SSC emissions at lower energy bands, these emissions decrease significantly at X-ray band with increasing $\gamma_{\text{min}}$. Even up to $\gamma_{\text{min}} = 100$, the predicted radio flux is significantly larger than the observed one. Similar to Mrk 421 (Chen 2017), it implies that the electron power-law distribution cannot extend down to such low energies (i.e., $\gamma_{\text{min}} \approx 30$). Hence, the observed X-ray concave feature of PKS 2155–304 cannot be produced by the low-energy part of the same electron

Figure 5. Simultaneous broadband SEDs of PKS 2155–304 from epochs 2009 to 2014. The gray data are the nonsimultaneous TeV data from H.E.S.S. Collaboration et al. (2012), corrected for EBL absorption (Franceschini et al. 2008).
population that produced the Fermi/LAT γ-rays. It can be noted that the SED of PKS 2155–304 during 2013 was also modeled by Madejski et al. (2016) using the one zone model and the derived minimum electron energy is $\gamma_{\text{min}} \sim 1$. However, it can noted that they are lacking the radio data in their SED modeling (see Figure 4 in Madejski et al. 2016).

The set of variability timescale may effect our results. Therefore, we set $T_{\text{var}} = 1$ day and model the SED again, which leads to smaller $R$ and larger $B$ values. In this case, the Doppler factor reaches very large values ($\delta = 47$ for epoch 2012 and $\delta = 58$ for epoch 2013). The modeling curves are presented in Figure 6 as dashed–dotted black lines. It can be seen that even in this extreme case, the predicted radio flux is larger than the observed one.

3.3.4. The Spine/Layer Jet

As detected by H.E.S.S., PKS 2155–304 has shown very rapid variability at the TeV band and the minimum variability timescale can be as small as $T_{\text{var}} = 3$–5 minutes (Aharonian et al. 2007), Another HSP BL Lac Mrk 501 also has minute variability at the TeV band as revealed by MAGIC Telescope, Albert et al. 2007). These fast variability of blazars indicate substantial substructure in their jets, which may be due to turbulence or as a result of magnetic reconnection (Ghisellini & Tavecchio 2008; Giannios et al. 2009; Reynoso et al. 2012). Rapid variability also implies a significant beaming effect of TeV HSP BL Lacs including PKS 2155–304. However, it is very interesting that the high resolution VLBA observations of PKS 2155–304 did not find superluminal motion of the central jet (Piner et al. 2008). One competitive possibility is that the jet has an inhomogeneous structure transverse to the jet axis, consisting of a fast “spine” that dominates the high-energy emission and a slower “layer” that dominates at lower frequencies (Giroletti et al. 2004; Ghisellini et al. 2005; Henri & Saugé 2006), which is consistent with the above substructure of the jet. The spine/layer jet model was initially studied by Sol et al. (1989). Irrespective of the origin of such transverse structures, their observational signatures are visible in the VLBI images of jets that are resolved in the transverse direction, either in the form of limb brightening or limb darkening (according to the region dominated by the radio emission). Observational signatures of limb brightening have been claimed in the VLBI images of the TeV sources such as Mrk 501 (Giroletti et al. 2004), Mrk 421 (Giroletti et al. 2006), and M87 (Kovalev et al. 2007). As suggested by Piner et al. (2008), VLBA images of PKS 2155–304 are not detected with sufficient resolution or dynamic range to discern structure transverse to the jet axis. Such observations are limited to the brighter sources (or to much more sensitive images of such sources).

Here, we model the broadband emission of PKS 2155–304 having concave X-ray spectra with the spine/layer model. We present a very brief introduction of the model, please see Chen (2017) for a detailed description. The spine/layer model used here is the same as that described in Ghisellini et al. (2005). For geometry, see Figure 1 of Ghisellini et al. (2005). The layer is assumed to be a hollow cylinder with external radius $R_2$, internal radius $R$, and width $\Delta R_1$ in the comoving frame of the layer. For the cylindrical spine, the radius is $R$ and the width is $\Delta R_1$. The spine and layer move with velocities $c \beta_s$ and $c \beta_l$, respectively, with $\Gamma_s$ and $\Gamma_l$ are the corresponding Lorentz factors. The relative velocity between the spine and the layer is then $\Gamma_{\text{rel}} = \Gamma_s \Gamma_l (1 - \beta_s \beta_l)$. Following Ghisellini et al. (2005), the radiation energy densities are considered as follows.

1. In the comoving frame of the layer, the radiation energy density $U_i^l = L_i^l / \left( \pi (R_2^2 - R^2) c \right)$ (slightly different from that of Ghisellini et al. 2005, to make sure that the radiation energy density is in the same format as that in the spine). In the frame of the spine, this radiation energy density will be boosted to $U_i^l = \Gamma_{\text{rel}}^2 U_i^l$.

2. In the comoving frame of the spine, the radiation energy within the spine is assumed to be $U_i^s = L_i^s / (\pi R^2 c)$. The radiation energy density observed in the frame of the layer will be boosted by $\Gamma_{\text{rel}}^2$ but also diluted (since

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Figure 6. One-zone SSC model for SED modeling of PKS 2155–304 for epochs 2012 (left panel) and 2013 (right panel). For both epochs, the red solid lines represents the total emissions with $\gamma_{\text{min}} = 10$, while the red dashed and dotted lines show the synchrotron and SSC emissions, respectively. The green dotted and blue dashed lines are for $\gamma_{\text{min}} = 30$ and 100, respectively. The dashed–dotted black lines are for SED modeling with $\Delta t = 1$ day (and therefore smaller $R$ and larger $B$, see the text for details). It can be seen that if one tries to fit the hard X-ray excess within the one-zone SSC model, the model will predict larger radio fluxes than the observed ones for both epochs.
the layer is larger than the spine) by a factor of
\[
\Delta R^\text{spine}_b \left/ \Delta R^\text{layer}_b = (\Delta R^\text{spine}_b / \Delta \gamma_0) / (\Delta R^\text{layer}_b / \Delta \gamma_0).
\]

The electron energy distributions in the spine and layer are all assumed to be broken power law plus log-parabolic model, as expressed in Equation (2), but with different parameters. In our modeling, we always assume \(\Delta R^\text{spine}_0 = 30 \Delta R^\text{layer}_0\), as given in Ghisellini et al. (2005). Then, we model the SEDs of epochs 2012 and 2013 by employing the spine/layer model. Figure 7 presents our SED modeling results, and the corresponding parameters are listed in Table 5. Geometry parameters for epochs 2012 and 2013 are \(R = 1.38 \times 10^{18} \text{ cm}, R_0 = 1.65 \times 10^{18} \text{ cm}, \Delta R^\text{spine}_0 = 2.29 \times 10^{17} \text{ cm} \) and \(R = 1.62 \times 10^{18} \text{ cm}, R_0 = 1.94 \times 10^{18} \text{ cm}, \Delta R^\text{layer}_0 = 2.69 \times 10^{17} \text{ cm}\), respectively. For both SEDs, red and blue lines represent the spine and layer emissions, respectively; dotted–dashed lines represents synchrotron emissions, dotted lines represent the SSC emissions, and dashed lines represents IC emissions of seed photons originated externally from the layer/spine. It can been seen that, similar to one-zone modeling, the synchrotron + SSC emissions of the spine can well reproduce almost the whole SED, except for the hard X-ray excess. The rise part of X-ray concave spectra can be successfully represented by the process of seed photons (produced from the layer) being IC scattered by the nonthermal electrons within the spine.

### 4. Discussion and Conclusions

We presented the results of spectral analysis of PKS 2155–304 using the XMM-Newton observations during the period of 2009–2014. We analyzed spectra of all of the pointings of PKS 2155–304 using single power-law and log-parabolic models. We found that the log-parabolic model better describes most of the observations. From Figure 4, it is clear that in most occasions there are

| Year | \(R (10^{17} \text{ cm})\) | \(\delta\) | \(B (10^{-3} \text{ Gs})\) | \(N_0\) | \(\gamma_0\) | \(\gamma_{\text{max}}\) | \(p\) | \(b\) |
|------|-----------------|------|-----------------|------|----------|----------|------|------|
| 2012-1 | 6.84 | 23.8 | 0.76 | 944 | 137256 | 100\(\gamma_0\) | 2.5 | 1.0 |
| 2012-2 | 1.36 | 47.1 | 1.05 | 5143 | 82704 | 100\(\gamma_0\) | 2.5 | 1.0 |
| 2013-1 | 8.19 | 28.3 | 0.96 | 150 | 80822 | 100\(\gamma_0\) | 2.4 | 0.75 |
| 2013-2 | 1.68 | 58.2 | 1.20 | 831 | 50412 | 100\(\gamma_0\) | 2.4 | 0.75 |

Note. The model curves for different \(\gamma_{\text{min}}\) are shown in Figure 6. 2012-1 and 2013-1 are SED parameters modeled with \(\Delta t = 10\) days and 2012-2 and 2013-2 are SED parameters modeled with \(\Delta t = 1\) day (see the text for details). \(R\): size of the emission region; \(\delta\): doppler factor; \(B\): magnetic field strength \(N_0\): normalized electron number density; \(\gamma_0\): broken electron energy; \(\gamma_{\text{max}}\): maximum electron energy \(p\): spectral index \(b\): curvature.

| Year | \(\theta (\degree)\) | \(\Gamma\) | \(\delta\) | \(B (10^{-3} \text{ Gs})\) | \(N_0\) | \(\gamma_0\) | \(\gamma_{\text{max}}\) | \(\gamma_{\text{max}}\) | \(p\) | \(b\) |
|------|-----------------|------|------|-----------------|------|----------|----------|----------|------|------|
| Spine(2012) | 1 | 12.5 | 23.8 | 0.75 | 2554 | 154004 | 3000 | 1000\(\gamma_0\) | 2.6 | 1.0 |
| Layer(2012) | 1 | 3.26 | 6.34 | 0.065 | 232 | 2646 | 2 | 1000\(\gamma_0\) | 2.0 | 1.0 |
| Spine(2013) | 1 | 3.49 | 6.80 | 0.076 | 133 | 2498 | 2 | 1000\(\gamma_0\) | 2.0 | 1.0 |
| Layer(2013) | 1 | 14.9 | 28.0 | 0.95 | 1070 | 143724 | 3000 | 1000\(\gamma_0\) | 2.6 | 1.0 |

Note. The model curves are shown in Figure 7. \(\theta (\degree)\): jet veiwing angle; \(\Gamma\): lorentz factor; \(\delta\): doppler factor; \(B\): magnetic field strength; \(N_0\): normalized electron number density; \(\gamma_0\): broken electron energy; \(\gamma_{\text{min}}\) and \(\gamma_{\text{max}}\): minimumum and maximum electron energy; \(b\): curvature.
residuals in the upward direction indicating flattening of the spectra above 6–7 KeV, but the spectral fits do not show negative curvature except in 2012. This pointing has the lowest flux among all of the observations studied here. Such a type of spectral flattening of PKS 2155–304 is also found in previous studies by Zhang (2008) and Foschini et al. (2008) and is interpreted as a mixture of the high energy tail of the synchrotron component, which is contaminated by the low-energy end of the IC component. Using the NuSTAR Satellite, Kataoka & Stawarz (2016) and Madejski et al. (2016) found the X-ray concave spectra of well known HBL Mrk 421 and PKS 2155–304 respectively. They explained this feature to be the power-law extension of the Fermi/LAT spectra. Since, the observations of Madejski et al. (2016) in 2013 are simultaneous with our observations of XMM-Newton, we included their data in our SED fitting.

In this way, we have significant X-ray concave spectra during epochs 2012 and 2013. Out of many possible explanations for the observed X-ray excess, one is that this excess is actually the high-energy tail of synchrotron X-ray emissions. However, it requires a spectral pile-up in electron distribution at the highest energies. This seems unlikely to work. The main reasons are as follows. (1) This high-energy pile-up bump requires the acceleration timescale to be equal to the radiative-loss timescale at the limit for the perfect confinement of electrons within the emission zone (Stawarz & Petrosian 2008). However, at lower electron energies, this scenario predicts a flat power tail, which is inconsistent with the X-ray observations of PKS 2155–304. (2) This high-energy tail can also be achieved by the electron high-energy pile-up due to the reduction of the IC cross-section in the KN regime (Moderski et al. 2005). However, it requires IC cooling dominating over synchrotron cooling. It is not consistent with the fact that PKS 2155–304 is almost totally dominated by synchrotron emission. Alternatively, it seems to be the low-energy tail of the Fermi/LAT γ-ray spectra. As discussed in Section 3.3.3, this possibility requires the minimal electron energy to be \( \gamma_{\text{min}} \lesssim 30 \). Such a lower electron energy predicts a very strong radio emission (after considering the SSA effect), which is larger than the observed radio flux. Therefore, the hard X-ray excess cannot be the low-energy tail of the Fermi/LAT γ-ray spectra.

In this paper, we explore the possibility of whether the origin of this concave X-ray feature is related to the spine/lower jet structure: a fast spine surrounded by a slower layer. The main reason for the choice of spine/lower layer model is due to the fact that PKS 2155–304 shows rapid variability and very slow radio proper motion (see Section 3.3.4), which indicates that its jet may be structured. Also, this model is able to produce IC SEDs that are significantly different from those produced by the one-zone model (Ghisellini et al. 2005; Sikora et al. 2016; Chen 2017). The spine/lower layer model can explain some inconsistencies between observations and the AGN standard unified model. According to the standard unified model, blazars and radio galaxies appear different due to difference in the viewing angles (Urry & Padovani 1995). Since the Doppler beaming factor depends significantly on the viewing angle, one can obtain the number distribution (number ratio between radio galaxies and blazars) as a function of the viewing angle. It is found that within the one zone model, this number ratio is inconsistent with observations (Chiaberge et al. 2000). This inconsistency can be explained using the spine/lower model, e.g., a faster-moving spine surrounded by a slower-moving layer (Chiaberge et al. 2000). In this model, sources having jets with smaller viewing angles with respect to our line of sight will be dominated by the faster spine (i.e., blazars), while the layer component will contribute more or even dominate the emissions in the sources having larger viewing angles (i.e., for radio galaxies). Hence, the spine/lower model predicts a larger number ratio between blazars and radio galaxies as compared to the one-zone model (Chiaberge et al. 2000). Also, the relative motion between the spine and the layer will amplify the photon energy density produced from the spine (layer) in the frame of the layer (spine) by \( \sim T_{\text{rel}}^2 \) (see Section 3.3.4), and, therefore, the IC emissions will be enhanced in this model as compared to one-zone model (Ghisellini et al. 2005).

We find that the spine emissions provide good modeling of the Multiwavelength SED of PKS 2155–304. However, similar to one zone modeling, the hard X-ray spectra is not well fitted by spine emissions. Similar to Mrk 421 (Chen 2017), the rising part of concave X-ray spectra can be well represented by the synchrotron photons from the layer being IC scattered by the spine electrons (see Figure 7).

Until now, about 49 HSP BL Lacs have been detected with VHE emissions. Also, the orphan flare is an interesting and less known phenomenon in blazar observations. The spine/lower layer model has been successfully used to explain the VHE γ-ray emission of blazars (see, e.g., Ghisellini et al. 2005; Tavecchio & Ghisellini 2008; Sikora et al. 2016). In order to explain the orphan flare in the γ-ray band, it is proposed that, when a faster-moving spine moves across a slower-moving layer/ring, the sudden increase of the energy density of external seed photons (produced from the layer) will be IC scattered by the spine electrons (MacDonald et al. 2015, 2016). The origin of the spine/lower structure is not yet clear. However, in some numerical simulations of Mizuno et al. (e.g., 2007) and Meliani et al. (e.g., 2010), it is found that it could arise directly from a jet launching process in which the external layer is ejected from the accretion disk while the central spine is fueled from the black hole ergosphere. Another possibility is the accumulation of the inflating toroidal magnetic field inside the accretion disk due to the magnetized accretion flow. It can produce a magnetic tower jet that presents a central helical magnetic field “spine” surrounded by a reversed magnetic field “sheath,” which could be a prototype of a spine/lower structure (see, e.g., Kato et al. 2004; Li et al. 2006).

The Multiwavelength SED of most of the HSP BL Lacs are well fitted by the one-zone model (e.g., Paggi et al. 2009; Zhang et al. 2012; Ghisellini et al. 2014; Yan et al. 2014; Ding et al. 2017). However, due to the limited sensitivity of the hard X-ray instruments, the rising/concave part of the X-ray band is not included in the fitting. If more sources like Mrk 421 and PKS 2155–304 are observed with hard X-ray spectra, it might be possible that their SED modeling underestimate their hard X-ray emissions and require the spine/lower model to better constrain them. For our SED modeling of PKS 2155–304, it should be noted that the model used is just a simple toy model, i.e., using two distinct regions (spine and layer) instead of continuing the distribution from jet axis to edge, although our modeled parameters are among the typical values of blazars (e.g., Ghisellini et al. 2010, 2014; Zhang et al. 2012).

\footnote{http://tevcat.uchicago.edu/}
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Appendix

Data Analysis Techniques

A.1. Excess Variance and Variability Amplitude

Each light curve has finite uncertainties $\sigma_{\text{err}}$ due to the measurement errors, which contribute to an additional variance. In order to subtract the uncertainties due to the individual flux measurements, we calculate the “excess variance” (Edelson et al. 2002; Vaughan et al. 2003), which is an estimator of the intrinsic source variance. The variance, after subtracting the excess contribution from the measurement errors is given as (Vaughan et al. 2003)

$$\sigma_{\text{XNS}}^2 = S^2 - \frac{1}{N} \sum_{i=1}^{N} \sigma_{\text{err}}^2,$$

where $\overline{\sigma_{\text{err}}^2}$ is the mean square error,

$$\overline{\sigma_{\text{err}}^2} = \frac{1}{N} \sum_{i=1}^{N} \sigma_{\text{err},i}^2.$$

The normalized excess variance is given by $\sigma_{\text{XNS}}^2 = \sigma_{\text{XNS}}^2/\overline{x}^2$ and the fractional root mean square variability amplitude ($F_{\text{var}}$; Edelson et al. 1990; Rodriguez-Pascual et al. 1997) is

$$F_{\text{var}} = \sqrt{\frac{\overline{x}^2 - \overline{\sigma_{\text{err}}^2}}{\overline{x}^2}}.$$

And the error on the fractional amplitude is given as

$$\text{err}(F_{\text{var}}) = \frac{1}{2F_{\text{var}}} \text{err}(\sigma_{\text{XNS}}^2) = \left( \frac{1}{2N} \cdot \frac{\overline{\sigma_{\text{err}}^2}}{\overline{x}^2 F_{\text{var}}} \right)^{\frac{1}{2}} + \left( \frac{1}{\overline{x}} \cdot \frac{\overline{\sigma_{\text{err}}^2}}{N} \right)^{\frac{1}{2}}.$$

We calculated $F_{\text{var}}$ for all of our light curves and the results are presented in Table 1.
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