Spectral Energy Distributions of the BL Lac PKS 2155–304 from XMM-Newton

Jai Bhagwan1,2, Alok C. Gupta1⋆ I. E. Papadakis3,4, Paul J. Wiita5

1Aryabhatta Research Institute of Observational Sciences (ARIES), Manora Peak, Nainital – 263002, India
2School of Studies in Physics & Astrophysics, Pt. Ravishankar Shukla University, Amanaka G.E. Road, Raipur – 492010, India
3Department of Physics and Institute of Theoretical and Computational Physics, University of Crete, GR-71003 Heraklion, Greece
4IESL, Foundation for Research and Technology, 71110 Heraklion, Greece
5Department of Physics, The College of New Jersey, PO Box 7718, Ewing, NJ 08628-0718, USA

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ABSTRACT
We have used all 20 archival XMM-Newton observations of PKS 2155 – 304 with simultaneous X-ray and UV/optical data to study its long term flux and spectral variability. We find significant variations, in all bands, on time scales of years with an rms amplitude of 35 – 45 per cent, though the optical/UV variations are not correlated with those in the X-ray. We constructed spectral energy distributions (SEDs) that span more than three orders of magnitude in frequency and we first fitted them with a log-parabolic model; such models have been applied many times in the past for this, and other, blazars. These fits were poor, so we then examined combined power-law and log-parabolic fits that are improvements. These models indicate that the optical/UV and X-ray flux variations are mainly driven by model normalization variations, but the X-ray band flux is also affected by spectral variations, as parametrized with the model “curvature” parameter, b. Overall, the energy at which the emitted power is maximum correlates positively with the total flux. As the spectrum shifts to higher frequencies, the spectral “curvature” increases, in contrast to what is expected if a single log-parabolic model were an acceptable representation of the broad band SEDs. Our results suggest that the optical/UV and X-ray emissions in this source may arise from different lepton populations.

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

1 INTRODUCTION

Blazars comprise a subclass of radio-loud active galactic nuclei that consist of BL Lacertae objects (BL Lacs) and flat spectrum radio quasars (FSRQs). These objects show flux and polarization variability on diverse time scales across the entire electromagnetic (EM) spectrum (Ulrich et al. 1997). According to the current paradigm, blazars have supermassive black holes at their centers that accrete material and produce relativistic jets that happen to be oriented close to our line of sight (Urry & Padovani 1995). The observed spectra of blazars are dominated by nonthermal radiation produced by relativistic electrons spiraling around the magnetic fields in relativistic jets (Blandford & Rees 1978; Urry & Padovani 1995).

The spectral energy distributions (SEDs) of blazars have two broad humps in the log(νFν) vs log(ν) representation (Ghisellini et al. 1997). The low energy SED hump peaks in a frequency ranging from sub-mm to soft X-ray bands is well explained by synchrotron emission from an ultra-relativistic electron population residing in the magnetic fields of the approaching relativistic jet (e.g., Maresch et al. 1992; Ghisellini et al. 1993; Hovatta et al. 2009; and references therein). The high energy SED hump that peaks in the MeV–TeV gamma-ray bands, is usually attributed to inverse Compton (IC) scattering of photons off those relativistic electrons. Depending on the peak frequency of synchrotron hump, νs, blazars are often further classified into three categories: low synchrotron-peaked (LSP) blazars have νs ≤ 1014 Hz, intermediate-synchrotron-peaked (ISP) have 1014 ≤ νs < 1015 Hz, and high synchrotron-peaked (HSP) blazars have νs > 1015 Hz (Abdo et al. 2010).

In the present work, we have studied the optical/UV and X-ray band variability of BL Lac PKS 2155 – 304 which

⋆ E-mail: acgupta30@gmail.com
is a HSP, PKS 2155 − 304 was one of the first recognized BL Lacs (Schwartz et al. 1979, Hewitt & Burbidge 1980) and is the brightest object in UV to TeV energies in the southern hemisphere. The redshift of PKS 2155 − 304 is 0.116 ± 0.002 as determined by optical spectroscopy of the galaxies in the BL Lac field (Falomo et al. 1993). This object has been studied on many occasions in single and multiple bands of the EM spectrum to search for variability, cross-correlated variability, SEDs and other properties of the source on diverse timescales (e.g., Shimmins & Bolton 1974; Carini & Miller 1992; Urry et al. 1993; Brinkmann et al. 1994; Marshall et al. 2001; Aharonian et al. 2005b; Dominici et al. 2006; Dolcini et al. 2007; Piner et al. 2008; Sakamoto et al. 2008; Kastendieck et al. 2011; Abramowski et al. 2012, and references therein). The first X-ray observation of PKS 2155 − 304 was taken by Schwartz et al. (1979) using HEAO-1. Chadwick et al. (1999) detected for the first time very high energy gamma-ray photons from this source using the Durham MK 6 telescope and thus classified it as a TeV blazar. There also are more recent claims of TeV emission from this source (Abramowski et al. 2012, and references therein). Simultaneous multi-band observations of the source from optical to X-ray bands using XMM-Newton data were reported by Zhang et al. (2006a, 2006b). Zhang (2008) found that the synchrotron emission of PKS 2155-304 peaked in the UV-EUV bands rather than the soft X-ray band. Gaur et al. (2010) searched for intra-day variability and quasi-periodic oscillations (QPOs) in the source using XMM-Newton data. Using International Ultraviolet Explorer observations in the UV band of PKS 2155-304 Urry et al. (1993) reported a possible short-lived QPO of ~0.7 day. More recently, stronger evidence for a ~4.6 hr QPO in this source on one occasion in XMM-Newton observations was reported (Lachowicz et al. 2009).

The blazar’s flux is rapidly variable in all the EM bands and is often accompanied by spectral changes as well. Changes in the SEDs are very likely associated with changes in the spectra of the emitting electrons. Modeling of broad-band SEDs of blazars is required to understand the extreme physical conditions inside the different emission regions. Flux variability studies can in principle play an important role in understanding the physical phenomena that are responsible for the low, high and outburst states of the source. Such studies are very important in discriminating between the models and applying tight constraints on model parameters, which are usually changed under the assumption that all other parameters are fixed (e.g., Mukherjee et al. 1999; Petry et al. 2000; Hartman et al. 2001). In the ideal case, such studies require large amounts of simultaneous data in various EM bands; unfortunately, this is severely lacking for blazars.

Thanks to the XMM-Newton satellite, which has instruments to observe simultaneously a specific source in optical, UV, and X-ray bands, this limitation can be partially overcome. On searching the complete archive of XMM-Newton, we found that there were 20 occasions on which data in at least one optical-UV band as well as X-ray bands were taken on same date for the BL Lac PKS 2155-304. These observations span a period of almost 12 years. They are thus ideal for studying the long-term flux and spectral variability of the source in the optical/UV/X-ray bands. We have used these data sets to generate simultaneous broad-band SEDs for the low-energy hump and we have fitted these SEDs with models to study the synchrotron emission mechanism and investigate how the various model parameters vary with the source flux.

This paper is structured as follows. In Section 2, we give a brief description of the XMM-Newton data reduction method. In Section 3 we discuss the long term variability in the light curves of different bands. We describe our SED modeling in Section 4. A discussion and our conclusions are given in Section 5.

2 THE XMM-NEWTON OBSERVATIONS AND DATA REDUCTION

Over the last ~12 years, the BL Lac PKS 2155 − 304 has been observed by XMM-Newton on 20 occasions. The journal of observations is given in Table 1. In the present work, we study the data obtained from the Optical Monitor (OM; Mason et al. 2001) and the European Photon Imaging Camera (EPIC) PN detector (Strüder et al. 2001). We did not consider the data from EPIC-MOS as the EPIC-PN data are more sensitive, and are less affected by photon pile-up effects. In all observations, the EPIC-PN detector was operated in the small window (SW) imaging mode. The OM has three optical and three ultraviolet (UV) filters and can provide data in the optical/UV bands simultaneously with the X-ray observations. In all, 20 observations with X-ray and at least one UV or optical band measurements are available in the archive.

We followed the standard procedure to reprocess the Observation Data File (ODF) with the XMM-Newton Science Analysis System (SAS) version 11.0.0 with the latest calibration files. We considered both single and double events (PATTERN ≤ 4) of good quality (FLAG = 0). The source counts in each observation were accumulated from a circular region centered on the source and with a radius of 33″ to 40″. These radii have been chosen to sample most of the PSF according to the observing mode. Background counts were accumulated from a circular region of radius 45″ on the CCD chip where the source was located and was the least affected from the source counts. The EPIC-PN redistribution matrix and effective areas were calculated with the rmfgen and arfgen tasks, respectively.

We checked for the high soft proton background periods which are caused by solar activity by generating a hard-band background light curve in the energy range 10−12 keV. We then defined as the “good time interval” (GTI) those times where the hard band count rate was less than 0.4 ct/sec. We also investigated the possibility for photon pile-up effects, which may be strong for a bright source such as PKS 2155−304. To this end, we used the epatplot SAS task. We found that nine observations were affected by photon pile-up. For these observations we excluded a circular region with a radius of 10″ centered on the source and we extracted the source counts in an annulus region which has an outer radius lying in the range of 33″ to 40″, depending on the position of the source on the chip.

We used the efuxer task to produce background subtracted, flux-calibrated EPIC-PN X-ray spectra in physical units of erg cm−2 s−1. These spectra can be used to
Table 1. Observation log of PKS 2155-304 with XMM-Newton EPIC/pn and optical monitor

| Revolution | Obs.ID | Exp.ID | Start Date | End Date | Duration (ks) | Pileup | OM Filters |
|------------|--------|--------|------------|----------|---------------|--------|-------------|
| 087        | 0124930101 | 087-1 | 2000-05-30 05:29:42 | 2000-05-30 22:28:11 | 37.9 | Yes | 3 |
| 087        | 0124930201 | 087-2 | 2000-05-31 00:30:51 | 2000-05-31 20:40:09 | 59.3 | Yes | 1 |
| 0174       | 0080940101 | 0174-1 | 2000-11-19 18:38:20 | 2000-11-20 11:26:51 | 57.2 | Yes | 1 |
| 0174       | 0080940301 | 0174-2 | 2000-11-20 12:53:01 | 2000-11-21 05:56:32 | 58.1 | Yes | 1 |
| 0362       | 0124930301 | 0362-1 | 2001-11-30 02:36:09 | 2001-12-01 04:19:46 | 44.6 | Yes | 1,2,3,4,5,6 |
| 0450       | 0124930501 | 0450-1 | 2002-05-24 09:31:62 | 2002-05-25 14:38:50 | 96.1 | Yes | 3,4,5,6 |
| 0545       | 0124930601 | 0545-1 | 2002-11-29 23:27:28 | 2002-12-01 07:18:43 | 56.8 | No | 1,2,3,4,5,6 |
| 0724       | 0158960101 | 0724-1 | 2003-11-23 00:46:22 | 2003-11-23 08:19:01 | 26.6 | No | 3,4 |
| 0908       | 0158960901 | 0908-1 | 2004-11-22 21:35:30 | 2004-11-23 05:37:29 | 28.4 | No | 4,5,6 |
| 0908       | 0158961001 | 0908-2 | 2004-11-23 19:45:55 | 2004-11-24 06:59:34 | 39.9 | No | 1,2,3,4 |
| 0993       | 0158961101 | 0993-1 | 2005-05-12 12:51:06 | 2005-05-12 20:52:56 | 26.1 | Yes | 1,2,3,4,5,6 |
| 1095       | 0158961301 | 1095-1 | 2005-11-30 20:34:04 | 2005-12-01 13:20:58 | 59.9 | Yes | 1,2,3,4,5,6 |
| 1171       | 0158961401 | 1171-1 | 2005-05-01 12:25:55 | 2005-06-02 06:26:09 | 64.3 | Yes | 1,2,3,4,5,6 |
| 1266       | 0411780101 | 1266-1 | 2006-11-07 00:22:47 | 2006-11-08 04:26:19 | 29.9 | No | 1,2,3,4,5,6 |
| 1349       | 0411780201 | 1349-1 | 2007-04-22 04:07:23 | 2007-04-22 22:59:14 | 58.5 | Yes | 1,2,3,4,5,6 |
| 1543       | 0411780301 | 1543-1 | 2008-05-12 15:02:34 | 2008-05-13 08:02:50 | 60.7 | Yes | 1,2,3,4,5,6 |
| 1734       | 0411780401 | 1734-1 | 2009-05-28 08:08:42 | 2009-05-29 02:09:02 | 64.3 | Yes | 1,2,3,4,5,6 |
| 1902       | 0411780501 | 1902-1 | 2010-04-28 23:47:42 | 2010-04-29 20:26:00 | 69.1 | No | 1,2,3,4,5,6 |
| 2084       | 0411780601 | 2084-1 | 2011-04-26 13:50:40 | 2011-04-27 07:34:18 | 63.3 | Yes | 1,2,3,4,5,6 |
| 2268       | 0411780701 | 2268-1 | 2012-04-28 00:48:26 | 2012-04-28 19:54:01 | 53.6 | No | 1,2,3,4,5,6 |

1 = UVW2, 2 = UVM2, 3 = UVW1, 4 = U, 5 = B, 6 = V

study the shape of the continuum X-ray emission in a model-independent way. On the other hand, their effective spectral resolution is degraded with respect to the intrinsic spectral resolution of EPIC-PN, but this is not a serious drawback in our case, as there are no narrow spectral features in the X-ray spectrum of this source. The final spectra are obtained from the OM data with the standard SAS routine omichain. This routine provides a combolist file with the source count rate and instrumental magnitudes for all the sources which are present in the field of view. The PKS 2155-304 fluxes corresponding to six optical/UV filters were corrected for galactic reddening (E_B-V = 0.019; Schlafly & Finkbeiner 2011) with the standard reddening correction curve by Cardelli et al. (1989) and applied using equation (2) in Roming et al. (2009).

3 THE OBSERVED LONG-TERM LIGHT CURVES

Fig. 1 shows the long term optical/UV/X-ray light curves of PKS 2155-304, using the observations we studied in this work. The points in this figure indicate the average count rate of each observation in the various OM filters, in the 0.6–2 keV (“soft”) and 2–10 keV (“hard”) band. Obviously, the source is highly variable in all bands, over the time period of ~12 years that the XMM–Newton observations were performed. We have estimated the rms variability amplitude (i.e. \sqrt{\sigma^2/m^2} where \sigma^2 and m are the variance, corrected for the experimental contribution, and mean of the light curve, respectively) for each light curve. The variability amplitude increased slightly going from the soft to hard X-ray bands but it decreased going from optical to UV bands. The values of rms variability amplitudes corresponding to the hard X-ray, soft X-ray, UVW2, UVM2, UVW1, U, B and V bands are 0.38, 0.35, 0.36, 0.38, 0.38, 0.39, 0.40 and 0.47, respectively.

On visual inspection, the observed variations in the optical bands are well correlated with the variations in the UV bands. The same appears to be true with the variations detected in the soft and hard X-ray bands. However, this is not the case when we compare the variability detected in the optical/UV bands and in the X-rays. Fig. 2 shows the UVW1 count rate plotted as functions of the 2–10 and 0.6–2 keV band measurements (upper and lower panels, respectively). Clearly, the flux variations in the UV and X-ray bands are not well correlated.

4 SED MODELING

Fig. 3 shows three optical/UV to X-ray SEDs of PKS 2155–304, using the mean optical and UV flux measurements in each XMM-Newton observation and the flux calibrated EPIC-PN data we described in the previous section. They are representative of all the observed SEDs. The spectra cover a frequency range of over three orders of magnitude. More importantly, as we have stressed earlier, the data...
Figure 1. Long term variability light curves for the XMM–Newton optical/UV and X-ray bands

in the optical and UV bands are simultaneous with those in
the X-ray bands. Given the shape of the SED in the optical/UV and X-ray bands, the low energy synchrotron peak
of this source is located between the energy bands sampled
by the XMM-Newton OM and EPIC-pn observations.

We fitted all SEDs with two models. The first one was a
log-parabolic model. We also considered the case of a spec-
tral model that has a power law shape at low energies, and
then acquires a log-parabola form at higher energies, following Massaro et al (2006) and Tramacere et al. (2009). We
describe below the best-fit results in both cases.

4.1 Log-parabolic fits

Log-parabolic models are parametrized with functions of the
form $F(E) = KE^{-(\Gamma+b\log(E))}$, where $F(E)$ is the source
flux in units of photons cm$^{-2}$ s$^{-1}$ keV$^{-1}$ at energy $E$ (see
e.g. Massaro et al. 2004). The $\Gamma$ parameter is the photon
index at 1 keV, and $b$ is a parameter that measures the
spectral curvature. Since in our case the data are directly
in flux density units (i.e. ergs cm$^{-2}$ s$^{-1}$), we decided to fit
them with a model of the form:

$$S(E) = K_S E^{-b[\log(E/E_p)]^2},$$

(1)
terminates the curvature of the model around $b$ spectral curvature parameter 
crease symmetrically around their peak frequency and $b$ normalization), which indicates the power at $E_p$.

3 indicate the best-fitting log-parabolic models to the SEDs in Fig. 3. The solid lines in the upper left hand panel of Fig. 4.2 Power-law plus log-parabolic (PLLP) fits

$K_S$: normalization constant (peak power) in units of $10^{-10}$ erg cm$^{-2}$ s$^{-1}$. $E_p$: energy at which the peak power is emitted in units of $10^{-2}$ keV

| Observation ID | $K_S$ | $b$ | $E_p$ | $\chi^2$/dof |
|---------------|------|-----|------|--------------|
| 0124930101    | 4.4  | 0.50| 5.0  | 3257/122     |
| 0124930201    | 3.6  | 0.49| 5.4  | 2489/122     |
| 0080940101    | 4.8  | 0.53| 4.4  | 3694/122     |
| 0080940301    | 4.3  | 0.54| 4.3  | 1423/122     |
| 0124930301    | 8.4  | 0.60| 5.5  | 85765/127    |
| 0124930501    | 3.8  | 0.49| 4.0  | 7850/124     |
| 0124930601    | 3.1  | 0.55| 4.5  | 213989/127   |
| 0158960101    | 3.3  | 0.55| 3.8  | 24141/123    |
| 0158960901    | 5.1  | 0.56| 3.3  | 15388/124    |
| 0158961001    | 4.6  | 0.59| 4.7  | 141156/125   |
| 0158961101    | 4.8  | 0.50| 4.6  | 42881/125    |
| 0158961301    | 6.1  | 0.50| 3.8  | 276580/127   |
| 0158961401    | 2.8  | 0.43| 2.6  | 120717/127   |
| 0411780101    | 3.5  | 0.40| 2.4  | 132211/127   |
| 0411780201    | 6.2  | 0.52| 3.9  | 28801/127    |
| 0411780301    | 6.0  | 0.52| 4.7  | 187076/127   |
| 0411780401    | 6.2  | 0.57| 4.0  | 286313/127   |
| 0411780501    | 3.0  | 0.54| 3.8  | 157672/127   |
| 0411780601    | 3.1  | 0.47| 4.1  | 175309/127   |
| 0411780701    | 1.5  | 0.55| 3.3  | 137475/126   |

$S(E) = E^2 F(E)$, and $K_S = E_p^2 F(E_p)$. The model has three free parameters: $E_p$, which is the energy where the peak power is emitted (in units of keV), $K_S$ (the model normalization), which indicates the power at $E_p$, and the spectral curvature parameter $b$.

Log-parabolic models best fit curved spectra which decrease symmetrically around their peak frequency and $b$ determines the curvature of the model around $E_p$. Similar models have been applied for a long time to parameterize blazar spectra in various energy bands. For example, Landau et al. (1986) analyzed the SEDs of a sample of blazars in millimeter to UV bands and found that the synchrotron emission of BL Lac sources were well fitted by a log-parabolic model. Krennrich et al. (1999) also used the log-parabolic model to describe the spectral curvature of Mrk 421 in the TeV band, while Giommi et al. (2002) applied it to the X-ray SEDs of 157 blazars observed by BeppoSAX.

The best model fit results are listed in Table 2, together with the best-fitting $\chi^2$ values (and the degrees of freedom − dof). Obviously, the best-model fits are not statistically acceptable for any of the 20 SEDs. (It is for this reason that we do not provide errors on the best-fit model parameter values.) Examples of the quality of the model fits are shown in Fig. 3. The solid lines in the upper left hand panel of Fig. 3 indicate the best-fitting log-parabolic models to the SEDs that are plotted in the same panel, and in the left lower panels of the same Figure we also plot the best-fit residuals.

Fig. 3 indicates that there are systematic discrepancies between the best-fitting models and the data at both high ($> 10^{18}$ Hz) and low ($< 10^{18}$ Hz) frequencies. These discrepancies could be the major reasons for the large $\chi^2$ values. In the high frequency end, the observed SED is always flatter than the best-fit models. This spectral flattening could be caused by the fact that the IC component starts contributing to the emission observed above $\sim 10^{18} \text{Hz}$ (i.e. $\sim 4 - 5 \text{keV}$). In the low frequency end, the observed flux is higher than the model flux in almost all cases (see for example the 22/04/2007 SED in Fig. 3).

There are three obvious physical possibilities for the discrepancy at lower frequencies. The first would be the contribution of the host galaxy emission, which should be more significant in the optical band. However, if this contamination were to be important the discrepancy should be much smaller at high flux states since we can safely assume the host galaxy emission is constant; this is not the case. The second possible physical explanation would be that the emission from the broad line region (BLR) and/or the underlying accretion disk is variable, and contributes significantly in the low frequency part of the observed SED.

A third possibility is that a log-parabolic model is not actually the true underlying physical model for the broad band, optical/UV up to X-ray SED of the source. For that reason, we also investigated the possibility that the low energy segment of the PKS 2155 − 304 UV to X-ray spectra follows a single power law and the log-parabolic bending becomes apparent only above a “critical”, turn-over energy, $E_c$.

4.2 Power-law plus log-parabolic (PLLP) fits

In the case of spectra in units of photons cm$^{-2}$ sec$^{-1}$ keV$^{-1}$ this model is defined as: $F(E) = K(E/E_p)^{\Gamma}$, at energies below $E_c$, and $F(E) = K(E/E_c)^{[-\Gamma+b \log(E/E_c)]}$ at energies

\[ K_S: \text{normalization constant (peak power) in units of } 10^{-10} \text{ erg cm}^{-2} \text{ s}^{-1}. \]

\[ E_p: \text{energy at which the peak power is emitted in units of } 10^{-2} \text{ keV}. \]
higher than $E_c$ ($\Gamma$ is the photon index). For spectra in flux density units (like our case), the above equations become:

\begin{align}
S(E) &= K_S(E/E_c)^{-\alpha'}, E \leq E_c, \\
S(E) &= K_S(E/E_c)^{[-\alpha' - b \log(E/E_c)]}, E > E_c,
\end{align}

where $K_S$ is the model normalization ($K_S = KE_c^\alpha$), and $\alpha' = \Gamma - 2$ is the spectral index of the SED in flux density units (i.e., $S(E) = E^\alpha F(E)$); we chose to denote the spectral index with $\alpha'$ in order to distinguish it from the usual spectral slope, $\alpha = \Gamma - 1$, which applies to SEDs in power over keV units). In this model, the energy where the peak power, $S_p$, is emitted is given by: $E_p = E_c 10^{-\alpha'/2b}$.

The best model fitting results are listed in Table 3, together with the best-fitting $\chi^2$ values and dof. Although the $\chi^2$ values have decreased significantly when compared to the $\chi^2$ values in the case of the log-parabolic best model fits, these models are still not statistically acceptable for any of the 20 SED. Examples of the quality of the model fits are also shown in Fig. 3. The solid lines in the upper right hand
the model does not fit well the X-ray data above.

In fact, the discrepancy is of the order of 10^3.

This time, the best-model fits do not over-predict the UV spectra. Indeed, the discrepancy between the best-fit model and the observed SEDs (i.e., the ratio (data-model)/data) is of the order of 100% in the X-ray band, and even smaller in the X-ray band (except from the 3.5 – 4 × 10^17 Hz region, where we observe discrepancies of the order of 10 – 20% in all spectra), even in the case of the SEDs with the highest χ^2 values. In fact, if we assume that the error of the SED points in all cases is equal to 5% of the SED values.

These reduced χ^2 values improve even more but are still not statistically acceptable. A major reason for this is the extremely small error bars in the optical/UV part of the spectra. Indeed, the discrepancy between the best-fit model and the observed SEDs (i.e., the ratio “data/model”) is of the order of ~5% in the UV band, and even smaller in the X-ray band (except from the 3.5 – 4 × 10^17 Hz region, where we observe discrepancies of the order of 10 – 20% in all spectra). In fact, if we assume that the error of the SED points in all cases is equal to 5% of the SED values, then the best-fit models to all spectra are now acceptable (with reduced χ^2 values of the order of 1 – 2). In this case, we can also estimate the 1σ error for the best-fit parameter values. These errors are indicated in Table 3 by the numbers in the parentheses next to the best-fit results in the case of the SED fits up to the 5 × 10^{17} Hz.

We used the PLLP best-fit results to investigate correlations between the best-fit model parameters and the observed UV and soft X-ray count rates. Fig. 4 shows plots of the best-fit model parameters with the observed UVW1 and 0.6-2 keV count rates (left and right panels, respectively). To quantify the correlation we used both the frequently used Pearson’s r as well as the non-parametric Kendall’s τ. Only the model normalization (i.e., K_S) is positively correlated with the UV flux (see lower left panel in Fig. 4). The correlation is statistically significant, and rather strong; Pearson’s r is 0.84 (τ = 0.65) and the probability that this value appears by chance is P_null = 2.5 × 10^{-5} (3 × 10^{-4}). In order to emphasize even more the correlation between the model normalization and the UV flux, the solid line in the bottom left panel of Fig. 4 indicates a straight line with a slope of unity. This is not the best fit to the data plotted in the same panel, but we plot it there in order to indicate that such a line appears to describe well the relation between the data plotted. Therefore, the UV flux variations could indeed be, to a large extent, proportional to the model normalization variations; i.e., to a first approximation, the UV flux is simply responding to the model normalization variations, without being affected by the other model parameters.

On the other hand, K_S does not correlate significantly with the soft X-ray flux (and neither does any of the other best-fit model parameter values). In the lower-right panel of Fig. 4 we also plot the one-to-one line. There may exist a rough positive correlation between the two quantities, but both Pearson’s r and Kendall’s τ imply that this correlation is not statistically significant. This result explains the lack of correlation we observe between the UV and X-ray fluxes (see Fig. 1). While the UV flux responds mainly to

| Observation ID   | K_S ±0.3 | ν_c ±0.9 | α ±0.1 | b ±0.3 | χ^2/dof |
|------------------|---------|---------|--------|--------|---------|
| 0124030101       | 2.2/3.1 | 2.3/5.0 | -0.82/0.64 | 0.54/0.62 | 1208/122 & 394/25 |
| 0124930201       | 1.7/2.0 | 2.0/2.3 | -0.86/0.92 | 0.52/0.57 | 1847/122 & 646/25 |
| 0080940101       | 2.8/3.2 | 2.4/3.0 | -0.77/0.76 | 0.56/0.62 | 1171/122 & 379/25 |
| 0080940301       | 2.5/3.0 | 2.3/2.9 | -0.81/0.79 | 0.58/0.64 | 1012/122 & 245/25 |
| 0124030601       | 4.8/5.2 | 11.6/14.2 | -0.40/0.39 | 0.70/0.80 | 5294/127 & 4058/30 |
| 0124930501       | 2.1/2.2 | 10.0/16.0 | -0.40/0.35 | 0.63/0.80 | 100/124 & 280/27 |
| 0158960101       | 1.5/1.6 | 16.6/20.6 | -0.24/0.23 | 0.71/0.83 | 8266/127 & 7030/30 |
| 0158960901       | 2.3/2.6 | 4.2/5.3 | -0.53/0.53 | 0.60/0.67 | 1028/123 & 412/27 |
| 0158961001       | 2.6/2.8 | 11.8/14.4 | -0.35/0.35 | 0.73/0.83 | 3310/125 & 2726/28 |
| 0124031101       | 3.2/3.6 | 5.1/6.8 | -0.49/0.49 | 0.55/0.64 | 5288/125 & 4686/29 |
| 0158961301       | 4.1/4.4 | 7.6/9.8 | -0.30/0.30 | 0.57/0.66 | 6965/127 & 5727/30 |
| 0158961401       | 2.0/2.1 | 6.6/9.3 | -0.15/0.15 | 0.48/0.58 | 4726/127 & 2782/30 |
| 0141780101       | 2.8/3.0 | 4.4/6.1 | -0.21/0.21 | 0.43/0.52 | 4533/127 & 3473/30 |
| 0141780201       | 3.8/3.8 | 11.8/16.8 | -0.18/0.16 | 0.61/0.75 | 4792/127 & 3100/31 |
| 0141780301       | 3.8/4.2 | 7.8/10.0 | -0.39/0.39 | 0.59/0.68 | 6042/127 & 4577/30 |
| 0141780401       | 3.8/4.0 | 8.9/10.8 | -0.32/0.32 | 0.66/0.74 | 5000/127 & 3980/31 |
| 0141780501       | 1.9/2.1 | 6.4/7.7 | -0.38/0.38 | 0.60/0.67 | 6452/127 & 5299/31 |
| 0141780601       | 2.0/2.0 | 10.0/12.7 | -0.26/0.25 | 0.55/0.64 | 8006/127 & 6354/31 |
| 0141780701       | 0.8/0.9 | 9.9/12.5 | -0.23/0.23 | 0.66/0.77 | 3721/126 & 3101/30 |

K_S: normalization constant in units of 10^{-10} erg cm^{-2} s^{-1}.
ν_c: turn-over frequency in units of 10^{15} Hz.

Table 3. The SED best-fitting parameter values for the power-law+log-parabolic model. (Numbers after the slash indicate the best fitting results in the case of the model fits to the SED data up to only 5 × 10^{17} Hz.)
the model normalization, the X-ray flux must also be significantly affected by spectral shape variations as well (i.e. variations of $b$ and $E_c$).

We also investigated the correlations within the model parameters. The only significant correlations that we found are those between $\nu_c$ (the turn-over frequency which corresponds to $E_c$) and $\alpha'$ (Pearson's $r = 0.73$, Kendall's $\tau = 0.5$, and $P_{null} = 2.2 \times 10^{-4}$ and $2.3 \times 10^{-3}$, respectively) and between $\nu_c$ and $b$ ($r = 0.80$, $\tau = 0.65$, $P_{null} = 2.7 \times 10^{-5}$, and $5.7 \times 10^{-5}$, respectively). Fig. 5 shows a plot of $\alpha'$ and $b$ versus $\nu_c$. Our results indicate that flatter and more curved spectra are associated with higher turn-over frequencies.

The upper panel in Fig. 6 shows a plot of the model curvature $b$ as a function of $\nu_p$ (the frequency at which the maximum power is emitted). Not surprisingly, given the correlation between $\nu_c$, $\alpha'$, and $b$, the parameters $b$ and $\nu_p$ are also strongly correlated. The correlation is positive, in the sense that as the peak power increases, the spectral curvature increases as well. The dashed line in the same panel indicates the best-fit line to the data (in the log–log space).
The best fitting PLLP $\alpha'$ and $b$ values plotted as a function of the turn-over frequency, $\nu_c$.

The fits have been performed using the "ordinary least-squares bisector" method of Isobe et al. (1990). The best-fit result indicates that: $b \propto \nu_c^{0.48 \pm 0.04}$. The error on the best-fit slope value indicate that the positive correlation between the parameters (in the log–log space) is significant at a level much higher than 3σ.

The lower panel in the same Figure shows $S_p$ (i.e. the maximum emitted power) plotted as a function of $\nu_p$. The two parameters appear to be loosely anti-correlated ($r = -0.21, \tau = -20$, but $P_{\text{null}} \sim 0.2 - 0.3$, in both cases). However, when we fit the data (in log-log space, we find that: $S_p \propto \nu_c^{-1.23 \pm 0.23}$). This result indicates that, if there is a correlation between these two parameters, it is an anti-correlation: as the maximum power emitted increases, the frequency at which it is emitted decreases.

**5 DISCUSSION AND CONCLUSIONS**

We have studied 20 archival XMM-Newton observations of PKS 2155 – 304 which have been performed in a period of over twelve years from 2000 to 2012. These observations can be useful in the study of the long-term optical/UV and X-ray variability of the source, not just because their number is large, but also because they allow us to study the flux and spectral variability of the source, over a broad frequency range, simultaneously. Our main results can be summarized as follows:

1. The source is variable at all bands on time scales of years. The amplitude of the rms variability is of the order of $\sim 35 - 45\%$ at all bands. We did not observe any extreme activity taking place during these observations. The variability amplitude slightly increases from the soft to the hard X-ray band, and decreases from the optical to the UV bands.

2. The optical/UV band fluxes increase and decrease in phase, i.e. the optical/UV band variations are well correlated. However, the X-ray and optical/UV fluxes are not correlated.

We then used (i) a log-parabolic (LP) model and (ii) a power-law plus log-parabolic (PLLP) model to fit the broad band SEDs. The LP model fits are not formally acceptable. Massaro et al. (2004) and Tramacere et al. (2009) have found that a LP model can well fit the optical/UV and X-ray spectra individually, but could not fit the combined optical/UV and X-ray bands. Our results are in agreement with their results.

The fits improve in the case of the PLLP model, but there are still significant discrepancies above $\sim 4$ keV in the X-rays, most probably due to the increased contribution of the IC component at larger energies. We repeated the fits using data up to $5 \times 10^{17}$ Hz only. These model fits appear to describe rather well the overall shape of the optical/UV/X-ray spectrum of the source at the $\sim 5\%$ level, i.e. the data/model ratio is typically between 0.95 and 1.05 at all energies up to $5 \times 10^{17}$ Hz). If we increase the error of the data points to this level, then the PLLP model fits the data well.

If we accept that a PLLP model can parametrize the optical/UV and X-ray SED of the source then our results from the SED fitting of all observations can be summarized as follows:

3. The turn-over frequency correlates positively with the model spectral slope, and with the curvature parameter,
b: as the turn-over energy increases, the spectrum steepens, and the curvature parameter increases.

(4) Due to the above mentioned correlations, the peak frequency, \( \nu_p \) and the curvature parameter \( b \) are also positively correlated. As \( \nu_p \) shifts to higher energies, the spectral curvature also increases following the relation: \( b \propto \nu_p^{-2} \).

(5) We do not observe a strong correlation between the peak power, \( S_p \), and the peak frequency, \( \nu_p \). If there is a relation between these two parameters, it is most probably an anti-correlation, in the sense that as the peak luminosity decreases, the peak frequency shifts to higher energies, roughly according to the relation: \( S_p \propto 1/\nu_p \).

Massaro et al. (2008) considered a sample of blazars and observed an anti-correlation between \( E_P \) and \( b \) for five TeV blazars including PKS 0548 – 322, 1H 1426 + 428, Mrk 501, and 1ES 1959 + 650. They also found a positive correlation between the spectrum peak power, \( S_p \), and \( E_p \). These correlations and anti-correlations were based on the results when a log-parabolic model was used to fit the X-ray spectra only. Clearly, our results regarding the relations between \( E_P, b \) and \( S_p \) are contrary to those reported by Massaro et al. (2008). However, they also studied PKS 2155-204, and found that the \( S_p \sim \nu_p \) and \( b \sim \nu_p \) relations in this object were different than the relations for the other objects in their sample results. In fact, the observational relations presented in their Fig. 8 are quite similar to our plots shown in Fig. 6.

From a phenomenological point of view, the PLLP model can be explained if the the electron distribution at low energies follows a power-law up to a turn-over energy, and a log-parabolic shape at higher energies. If that is the case, our results indicate that this low-energy power-law branch is always present in PKS 2155-304. Furthermore, we can constrain the typical slope of the power-law energy distribution of the electrons, \( s \), using the the well-known relation between \( s \) and \( \alpha' \): \( \alpha' = (s-3)/2 \). For the mean spectral index value of \( \alpha' \sim 0.41 \) in our case, we estimate that \( s \sim 2.2 \). This slope is fully consistent with predictions of models which assume first-order Fermi acceleration as being the primary acceleration mechanism in most collisionless magnetohydrodynamic (MHD) shocks, as has been shown both analytically (e.g. Bell 1978, Kirk et al. 2000) and numerically (e.g. Bednarz & Ostrowski 1998; Baring et al. 1999; Ellison & Double 2004).

The presence of the log-parabolic branch in the electron distribution can be explained as in Massaro et al. (2004). These authors have shown that when the acceleration efficiency of particles is inversely proportional to the energy itself, then the energy distribution approaches a log-parabolic shape. They proposed that the log-parabolic spectra are naturally produced when the statistical acceleration probability is inversely proportional to the energy of mono-energetic particles injection under a Fokker-Planck equation with a momentum-diffusion term. Kardashev et al. (1962) have shown that the curvature term \( r \) is inversely proportional to the diffusion term \( D \) and the time \( t: r \propto D^{-1/2} \).

This relation leads to the following connection between the peak frequency, the peak energy of the electron distribution, \( \gamma_p \), and the spectral curvature \( b \) (Eqn. 5 of Tramacere et al. 2009): \( \ln(E_P) = 2\ln(\gamma_P) + 3/5b \).

Hence both the fractional acceleration gain term, \( \epsilon \), and the momentum diffusion term, \( D \) predict an anti-correlation between \( E_P \) and \( b \). However, this opposite to what we observe. As we showed in Section 4, if there is a relation between \( E_P \) and \( b \), this is a positive, and not a negative one.

The inability of the model to provide acceptable fits to the broad band optical/UV/X-ray SEDs of PKS 2155 – 304, as well as the positive correlation between \( E_P \) and \( b \) that we observe, perhaps indicates that the optical/UV and X-ray emission in this source are produced by two different populations of leptons. Optical/UV emission may be produced by slow leptons and the X-ray emission may due to emission from much more energetic leptons, which may have been accelerated through the energy dependent particle acceleration mechanism. This possibility could also explain the fact that the optical/UV bands are well correlated with each other but not correlated with X-ray bands. Another possibility for the positive correlation between \( E_P \) and \( b \) can arise within the stochastic acceleration framework if the cooling losses successfully compete with the acceleration and diffusion components (Tramacere et al. 2011). However, only if we can analyze more SEDs, preferably including a wider range of EM bands, might the correlations between these parameters be clarified. That would definitely increase our understanding of the emission processes that dominate the spectra of blazars.

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