The X-ray behaviour of the high-energy peaked BL Lacertae source PKS 2155–304 in the 0.3–10 keV band

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ABSTRACT
We present the results of our monitoring of the high-energy peaked BL Lac object PKS 2155–304 by the Swift/X-Ray Telescope (XRT) during 2005–2012. Our timing study shows that the source was highly variable both on longer (weeks-to-months) and intra-day time-scales, up to a factor of 7 in flux, and 30 per cent in fractional variability amplitudes, with no periodic variations. The X-ray spectra are mainly curved with broad ranges of photon index, curvature parameter, and hardness ratio which exhibit significant variability with the flux on different time-scales. Our study of multi-wavelength cross-correlations has revealed that the one-zone SSC scenario seems to be valid for the most optical-to-gamma-ray flares observed during 2006–2012. An ‘orphan’ X-ray flare with no counterpart in other spectral bands suggests the existence of different electron populations. Based on the absence of a correlation between photon index and curvature parameter (expected from the energy-dependent acceleration probability scenario), the observed distribution of curvature parameter from the XRT spectra peaking at $b = 0.37$, and the observed anti-correlation between the curvature parameter and the 0.3–10 keV flux (i.e. lower curvatures in flaring states), we conclude that the most likely mechanism responsible for producing X-ray emission during the flares is the stochastic acceleration of the electrons.

Key words: BL Lacertae objects: individual: PKS 2155–304.

1 INTRODUCTION

The BL Lacertae objects (BLLs) constitute a rather extreme class of active galactic nuclei (AGNs). They show a rapid variability at all frequencies, high and variable radio and optical polarization, compact and flat-spectrum radio emission, superluminal motion, smooth and broad non-thermal continuum covering the electromagnetic spectrum from radio to $\gamma$-rays, and absence of emission lines in the optical band (Piranomonte et al. 2007). In the framework of the unified scheme for radio-loud AGNs, these features are explained by a relativistic bulk motion of the emitting region towards the observer (Urry & Padovani 1995). Their spectral energy distribution (SED) is characterized by a double bump structure in the log $\nu F_\nu$ – log $\nu$ representation. The lower-frequency component is explained by a synchrotron radiation emitted by relativistic electrons in the jet, pointed to the observer, while an inverse Compton (IC) scattering of synchrotron photons by the same electron population is thought to be a source of the high-frequency bump (Celotti & Ghisellini 2008).

A flux variability in BLLs provides the clearest evidence for non-stationary dynamic processes occurring near their central engines (e.g. Pian et al. 1997). Its investigation in different spectral bands is therefore a powerful tool to study the innermost regions of these objects and the emission mechanisms creating their energy budget. The variability time-scales strongly constrain the sizes of the emitting regions, through the light-travel argument (Tramacere et al. 2009, hereinafter T09).

The X-ray emission from the HBL sources (i.e. BLLs with a synchrotron component peaking in at the UV-X-ray frequencies; Abdo et al. 2010) is thought to be a high-energy tail of synchrotron emission component produced in the innermost parts of a relativistic jet where the most rapid variability is expected (e.g. Zhang et al. 2005). The light curves, derived from the observations performed by various X-ray instruments, show an erratic and unpredictable behaviour by changing the flare strength and duration from event to event (e.g. Tanihata et al. 2001; Cui 2004). While the investigation of X-ray flux variability is important to discriminate among the possible underlying physical processes, we need to study a large amount of the data to obtain meaningful average properties of the BLL light curves.

The multiwavelength campaigns, performed for the bright BLLs, have shown that the X-ray and VHE emissions are generally highly

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correlated. For example, the HEGRA and RXTE–ASM observations of Mrk 501 showed a significant inter-band correlation with no time-lag (Aharonian et al. 1999). The highly correlated TeV and X-ray variations in Mrk 421 were reported by Fossati et al. (2008) and Giebels, Dubus & Khelifi (2007), with no evidence of an inter-band lag. These results provide a strong support to the idea that the same electron population in the same physical region is responsible for the emission in both energy bands (so-called one-zone SSC scenario). However, the same campaigns have also unveiled a more complex and puzzling behaviour, which poses a challenge to the aforementioned scenario. Namely, some VHE flares without any visible X-ray counterpart have been recorded (so-called ‘orphan’ flares). The clearest example was provided by IES 1959+650 when a strong and rapid TeV flare was not accompanied by X-ray variations (Krawczynski et al. 2004). Furthermore, Mrk 421 exhibited a quadratic relation between VHE and X-ray flux variations during both the rising and decaying phases of the flare (Fossati et al. 2008), and a cubic relation between the VHE and X-ray fluxes was detected during the decaying phase of the prominent TeV flare (2006 July) in PKS 2155–304 (Aharonian et al. 2009, hereafter A09). These correlations pose a serious challenge to the emission models since they are not expected if the source is in the Klein–Nishina (KN) regime (see Fossati et al. 2008; A09).

X-ray flux variability in BL Lacs is often accompanied by considerable changes in their spectral shape. Useful information about the blazar spectral evolution during the flare can be obtained by analysing the hysteresis patterns in the hardness ratio (HR)–flux or photon index–flux plane which may trace a clockwise (CW) loop with a flux evolution if the flares at higher frequencies advance those at lower ones (so-called soft lag). In that case, the electrons are accelerated rapidly compared to the rate they cool, the spectra typically harden during the phase of a rising flux, and soften during the flux decay. In contrast, if the acceleration and cooling time-scales are almost equal, the loops are expected to be counter-clockwise (CCW) with a possible hard lag (Cui 2004). Different studies have revealed a very complex spectral evolution in HBLs with both CW and CCW patterns (see e.g. T09). Different authors also reported the intrinsically curved spectra for HBLs (e.g. Massaro et al. 2004, hereafter M04; Massaro et al. 2008, hereafter M08; Perlman et al. 2005) that could not be simply explained as a result of a radiative cooling of high-energy electrons, responsible for the synchrotron and IC emission, but rather related to their acceleration mechanisms.

The HBL source PKS 2155–304 ($z = 0.117$; Bowyer et al. 1984) was first detected in X-rays by the HEAO-1 mission (Agrawal & Rieger 1979). It was found variable by the Einstein Observatory (Urry, Mushotzky & Holt 1986), EXOSAT (Morini et al. 1986), Ginga (Sembay et al. 1993), ROSAT (Brinkmann et al. 1994, 2000). The 2–10 keV flux doubling on the 30 ks time-scale was detected by the ASCA mission in 1994 May with 1–2 d lag of UV light curves with respect to the X-ray one (Kataoka et al. 2000). This mission also revealed a flux increase by a factor of 3, superimposed by the intra-day fluctuations by 30–50 per cent (Tanihata et al. 2001). The BeppoSAX 1996–1999 observations showed the flux variations by 20–30 per cent around the mean flux with time-scales down to 10 ks in the 0.1–100 keV energy band (Giommi et al. 1998), and a close inter-band correlation with a tendency of increasing amplitude towards higher energies was evident (Zhang et al. 1999, 2002, hereafter Z02). The 2000 May 30–31 pointing of XMM–Newton showed flux changes on the sub-hour time-scales whose amplitudes increased towards the higher-energy part of the 0.1–12 keV energy band and no significant inter-band lag was detected (Edelson et al. 2001).

Lachowicz et al. (2009) reported a possible detection of the 4.6 h quasi-periodic oscillation of the 0.3–10 keV emission from the 2006 May 1 pointing of this telescope. Osterman et al. (2007) found two consecutive X-ray flares of 4–6 d durations from the 2004 August campaign of the RXTE-PCA, accompanied by a correlated variability in the optical/UV bands.

The TeV-detection of PKS 2155–304 was performed during the 1996–1997 observations with the Durham telescopes. The VHE and X-ray fluxes (from the RXTE-ASM observations) showed a correlation with each other (Chadwick et al. 1999). The source was confirmed as a VHE-emitter by HESS during the 2002 July–2003 September campaign when it showed a variability on the time-scales of months, days and hours, not correlated with that in the 2–10 keV energy band (Aharonian et al. 2005). During the extreme VHE outburst by a factor of 22 on 2006 July 29, observed intensively by HESS, extremely fast fluctuations were detected. The VHE and X-ray (PCA, Swift-XRT and Chandra) variabilities were strongly correlated, with no evidence of time lags (Aharonian et al. 2007; A09).

In this paper, we analyse the 0.3–10 keV band observations of PKS 2155–304 performed by the X-Ray Telescope (XRT; Burrows et al. 2005) onboard the Swift satellite (Gehrels et al. 2004) during 2005–2012. Thanks to the unique characteristics, good photon statistics and low background counts of this instrument, we can investigate a flux variability on different time-scales from minutes to years, obtain high-quality spectra for the majority of the observations, derive different spectral parameters, and study their timing behaviour. The contemporaneous available TeV, High-energy (Fermi-LAT), UV-optical-IR (Swift–UVOT and SMARTS) observations are also examined to search for the inter-band correlations.

The paper is organized as follows. Section 2 describes the data processing and analysis procedure. In Section 3, we provide the results of a timing analysis and those for the X-ray spectroscopy in Section 4. The inter-band cross-correlations are presented in Section 5. We discuss our results in Section 6 and provide our conclusions in Section 7.

## 2 OBSERVATIONS AND DATA REDUCTION

### 2.1 X-ray data

The observations were performed by the XRT between 2005 November 17 and 2012 October 14. We retrieved the data from the publicly available archive, maintained by HEASARC.¹ We chose the Level 1 unscreened event files which were reduced via the XRTPipeline script (version 0.12.6) using the standard filtering criteria with the latest calibration files, available at the Swift CALDB 4.1.3. We selected the events with the 0–2 grades for the Windowed Timing (WT) mode, whereas the range of 0–12 was used for the Photon Counting (PC) observations.

The source and background light curves were extracted with the XSELECT package (version v2.4b). We used an outer radius of 20–30 pixels for event extraction regions depending on the source

¹ [http://heasarc.gsfc.nasa.gov/docs/archive.html](http://heasarc.gsfc.nasa.gov/docs/archive.html)
brightness. The source count rates were always above 0.5 cts s\(^{-1}\) when the PC mode data are significantly affected by a pile-up in the inner part of the PSF (see Romano et al. 2006, and references therein). We performed a pile-up correction by determining the radius of the affected core of PSF, comparing the observed PSF profile with the analytical model derived by Moretti et al. (2005), and excluded the events within an annular region with inner radius of 4–6 pixels depending on the source brightness. Note that for the flux range of 0–100 cts s\(^{-1}\), no pile-up is expected for the WT mode (Romano et al. 2006). Since the fluxes from PKS 2155–304 were significantly lower compared to this upper limit, no correction for the pile-up was necessary. The source light curve was then corrected using the \texttt{xrtlccorr} task for the resultant loss of effective area (due to the extraction region geometry), bad/hot pixels, pileup, and vignetting. The background was subtracted from the source counts using the \texttt{xronos} task \texttt{lcurve} which allows to bin a light curve within the certain time intervals to ensure the minimum of 20 counts per bin (necessary to use the \(\chi^2\) statistics). For the typical fluxes from our target, the 40 s bins were enough in the faintest states and the 2 s bins – during the brightest states for this purpose. However, we used the 1-min bins to have a relatively high signal-to-noise ratio of 8–10 when searching for the fast intra-day variability events.

We extracted the events for a spectral analysis with \texttt{xselect} in the same regions used for a light-curve generation. The exposure maps were created by \texttt{xrpipeline}, and the corresponding ancillary response files (ARFs) were generated with the \texttt{xrtpmkarf} task to account for the different extraction regions, vignetting, PSF corrections, and CCD defects. We used the latest spectral response matrices from the CALDB. The instrumental channels were combined to include at least 20 photons per bin using the \texttt{grippha} task. The 0.3–10 keV spectra were analysed with the \texttt{xspec} package (version 12.7.0). For some long WT observations with some angles between the images from different orbits, we extracted the spectra separately from each one. Furthermore, the spectra from the observations with an intra-day flux variability were also split into orbit-resolved ones to trace the evolution of spectral parameters along with the flux changes.

### 2.2 Optical and UV data

The UVOT observations were taken in the bands \(V\), \(B\), \(U\), \(UVW1\), \(UVM2\), and \(UVW2\) simultaneously with those performed by the XRT. The sky-corrected images were retrieved from the \textit{Swift} archive. The \texttt{uvotsource} tool was used to extract counts, correct for coincidence losses, apply background subtraction, calculate the corresponding magnitudes. The measurements were performed using the 6 arcsec radius source aperture for \(V\), \(B\), \(U\) bands, and the 15 arcsec radius – for \(UVW1\), \(UVM2\), \(UVW2\) bands to take properly into account wider PSFs. The magnitudes were then de-reddened applying \(E(B-V) = 0.022\), and the \(A_I/E(B-V)\) values calculated using the interstellar extinction curves provided in Fitzpatrick & Massa (2007), and the effective wavelength of each UVOT filters was taken from Poole et al. (2008). We converted them into linear fluxes adopting the latest photometric zero-points for each band provided in Breeveld et al. (2011). Several observations from the 2006 July–August campaign revealed the source brighter than 12.68 mag and 11.91 mag in the \(B\) and \(U\) bands, respectively. In these cases, the \texttt{uvotsource} tool only gives a lower limit to the brightness and we adopted the method of a magnitude estimation via the read-out streaks developed by Page et al. (2013).

### 2.3 High-energy \(\gamma\)-ray data

The contemporaneous 100 MeV–300 GeV fluxes were extracted from the daily-binned \textit{Fermi}-LAT observations (starting since 2008 August 5) using a circular region of the 10\(^{\circ}\) radius, centred on the location of PKS 2155–304, and processed via the \textit{Fermi} Science Tools package (version v9r31p1). A cut on the zenith angle (>105\(^{\circ}\)) was applied to reduce contamination from the Earth-albedo \(\gamma\)-rays. The background model, used to extract the \(\gamma\)-ray signal, includes the Galactic diffuse emission and an isotropic component. The model, adopted for the Galactic component, is given by the file \texttt{gll\_jem\_v05\_fit}, and the isotropic component (the sum of extragalactic diffuse emission and the residual charged particle background) was parametrized by the file \texttt{iso\_source\_v05}. The unbinned maximum likelihood analysis with Python was adopted to derive spectral fits and photon fluxes using the post-launch instrument response functions \texttt{p7rep\_source\_v15}. The source detection significance \(\sigma\) is related to the likelihood test statistic (TS) as \(\sigma = \sqrt{(TS)^2/2}\). In the case the daily-binned observation showed TS < 9, we used larger bins centred on the XRT observation to detect the source above the 3\(\sigma\) threshold. The \texttt{likeSED} tool was used to extract the spectral points in the 0.1–300 GeV energy band.

Throughout this paper, the errors are quoted at the 90 per cent confidence for the one parameter of interest \(\Delta_{\gamma}\ = 2.71\) unless otherwise stated.

### 3 TIMING ANALYSIS

Fig. 1 presents the 0.3–10 keV historical light curve of PKS 2155–304 from the XRT observations, constructed on the basis of point-dedgedge flux values (98 data points corresponding to the total 203.6 ks exposure time). The information about each pointing and the measurement results are provided in Table 1.\(^2\) We have also included the 0.1–300 GeV flux values from the contemporaneous LAT observations in this table. The results of UVOT observations are presented in Table 2 where the de-reddened magnitudes and corresponding fluxes are provided for each band.

In Table 3, we provide the basic results of a timing analysis performed in the XRT and LAT bands in different periods. For each flare, we calculated the fractional root mean square (rms) variability amplitude as (Vaughan et al. 2003)

\[
F_{\text{var}} = 100 \sqrt{S^2 - \left(\sigma_{\text{var}}^2\right) / \langle F \rangle^2} \text{ per cent,} \tag{1}
\]

with \(S^2\) the sample variance, \(\sigma_{\text{var}}^2\) the mean square error, and \(\langle F \rangle\) the mean flux. Along with this quantity, we also derived the value of the absolute amplitude of a flux variability as follows (Heidt & Wagner 1996)

\[
A = \sqrt{(F_{\text{max}} - F_{\text{min}})^2 - 2\sigma_{\text{var}}^2}. \tag{2}
\]

#### 3.1 Flux variability during 2006–2008

In Period 1 (see Table 3), the source was mainly observed in 2006 April, when the highest X-ray and \(R\)-band fluxes (obtained with the \textit{ROSETTA-IIc} telescope) were recorded on MJD = 53846, followed

\(^2\) \texttt{fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/python\_tutorial.html}

\(^3\) The printed version of the paper presents the extracts from Tables 1, 2, 4, 5 and Figs 2, 3, 6, 7, 10. Their full versions are available online. Fig. 11 is completely included in the online material.
by a decay in both bands. The most intensive XRT campaign was performed in Period 2 (see Table 3), since the extreme VHE flare of 2006 July 28–29. The highest 0.3–10 keV flux was observed in the case of the July 29 pointing (MJD = 53946). This WT observation was performed during four separate orbits whose respective images are separated by significant angles. Therefore, we have split the event file into those corresponding to each orbit to avoid the derivation of incorrect flux values for the source and background. The exposure during the first orbit was very short (5 s) and we did not perform its analysis. The events from the second and fourth orbits were also neglected since the points corresponding to highest counts are situated just at the end of the image, and this may lead to the large uncertainties in the PSF reconstruction. Only the events from the third orbit were used for the analysis – we had managed to select an annular area with 18 pixel radius centred on the pixel with maximum count. The source did not exhibit significant flux changes during the 1.64 ks interval – the reduced chi-square is only 0.926 with 26 d.o.f. (see Section 3.5 for the flux variability detection criterion, used throughout this paper). After this pointing, we observe a gradual decay in the 0.3–10 keV light curve, superimposed by some short-term outbursts by $F_{\text{var}} = 22.6–37.3$ per cent.

A high brightness level was also the case in the UVOT bands and at 3.5 cm in the epoch of highest X-ray flux. The corresponding light curves show a decay till MJD = 53953 (before the second short-term X-ray outburst) but they do not follow a long-term

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4 Since the fluxes of PKS 2155–304 from the UVOT bands are highly correlated, the corresponding light curves are similar to each other. Therefore, the plots, corresponding to different epochs in Fig. 1, contain only those constructed using the de-reddened magnitudes from the highest (UVW2) and the lowest (V) energy bands.
decay trend in opposite to that from the X-rays – we observe the fluctuations around the mean flux value from the first outburst. Nevertheless, the radio flux shows a long-term increase with minor fluctuations till the end of the campaign.

The last panel of Period 2 plot shows a temporal evolution of VHE flux from the HESS observations (taken from Abramowski et al. 2012). After July 29,\textsuperscript{5} it decayed to its low level by a factor of $\sim 100$ and showed a relatively minor fluctuation centred on

\textsuperscript{5}Since the HESS observations of July 28–29 are analysed in details in A09 and Abramowski et al. (2012), we omit them from this study.
Table 1. Extract from the summary of the Swift-XRT observations. The columns are as follows: (1) – observation ID; (2) and (3) – observation beginning and end, respectively (in UTC); (4) – exposure time (in seconds); (5) – observation mode; (6), (7), (8), and (9) – average value of the observed flux with its error (in cts s\(^{-1}\)), reduced \(\chi^2\) and corresponding d.o.f., existence of a variability during the observation, respectively; (9) – the contemporaneous 0.1–300 GeV flux (in the units of ph cm\(^{-2}\) s\(^{-1}\)), and the corresponding TS value is given in Column 10.

<table>
<thead>
<tr>
<th>ObsID</th>
<th>Start time</th>
<th>End time</th>
<th>Exp. (s)</th>
<th>Mode</th>
<th>Mean flux</th>
<th>(\chi^2)/d.o.f.</th>
<th>Var.</th>
<th>(F_{\text{LAT}})</th>
<th>TS</th>
</tr>
</thead>
<tbody>
<tr>
<td>35027001</td>
<td>12.58(0.03)</td>
<td>34.04</td>
<td>12.59(0.05)</td>
<td>37.33</td>
<td>11.80(0.04)</td>
<td>27.54</td>
<td>11.54(0.04)</td>
<td>21.68</td>
<td>11.47(0.03)</td>
</tr>
<tr>
<td>35027002</td>
<td>12.84(0.04)</td>
<td>26.79</td>
<td>12.60(0.09)</td>
<td>36.98</td>
<td>11.87(0.11)</td>
<td>25.82</td>
<td>11.80(0.05)</td>
<td>17.06</td>
<td>11.90(0.04)</td>
</tr>
<tr>
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<td>13.03(0.04)</td>
<td>22.49</td>
<td>12.75(0.07)</td>
<td>32.21</td>
<td>12.07(0.07)</td>
<td>21.48</td>
<td>12.03(0.05)</td>
<td>13.80</td>
<td>12.05(0.04)</td>
</tr>
<tr>
<td>35027004</td>
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<td>27.29</td>
<td>12.59(0.05)</td>
<td>37.33</td>
<td>11.80(0.04)</td>
<td>27.54</td>
<td>11.54(0.04)</td>
<td>21.68</td>
<td>11.47(0.03)</td>
</tr>
</tbody>
</table>

Table 2. Extract from the results of the Swift-UVOT observations. The flux values in each band are given in the units of mJy.

<table>
<thead>
<tr>
<th>ObsID</th>
<th>V</th>
<th>B</th>
<th>U</th>
<th>UVW1</th>
<th>UVM2</th>
<th>UVW2</th>
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<tr>
<td>35027001</td>
<td>12.58(0.03)</td>
<td>34.04</td>
<td>12.59(0.05)</td>
<td>37.33</td>
<td>11.80(0.04)</td>
<td>27.54</td>
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<td>11.87(0.11)</td>
<td>25.82</td>
</tr>
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<td>22.49</td>
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<td>35027004</td>
<td>12.82(0.03)</td>
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<td>12.59(0.05)</td>
<td>37.33</td>
<td>11.80(0.04)</td>
<td>27.54</td>
</tr>
</tbody>
</table>

Table 3. Summary of the XRT and LAT observations in different periods (Column 1). Column 3: number of X-ray flares in given period; Columns (4)–(7): maximum and minimum 0.3–10 keV fluxes (in cts s\(^{-1}\)), \(F_{\text{var}}\) (per cent) and \(A\) (mag.) for each flare, respectively; Column 8: number of short-term HE outbursts in the epochs of high X-ray flux. Their corresponding maximum and minimum fluxes (in \(10^{-9}\) ph cm\(^{-2}\) s\(^{-1}\)), and \(F_{\text{var}}\) values are provided in Columns 9–11, respectively (separately for each outburst, or the range of maximum flux is provided when \(N_{\text{var}} > 2\)).

<table>
<thead>
<tr>
<th>Per. Dates (1)</th>
<th>Nfl (2)</th>
<th>(F_{\text{max}}) (4)</th>
<th>(F_{\text{min}}) (5)</th>
<th>(F_{\text{var}}) (6)</th>
<th>(A) (7)</th>
<th>(N_{\text{var}}) (8)</th>
<th>(F_{\text{max}}) (9)</th>
<th>(F_{\text{min}}) (10)</th>
<th>(F_{\text{var}}) (11)</th>
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</thead>
<tbody>
<tr>
<td>2005 Nov 17–2006 Apr 30</td>
<td>1</td>
<td>4.69</td>
<td>2.28</td>
<td>27.5</td>
<td>2.40</td>
<td>–</td>
<td>–</td>
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<td>–</td>
</tr>
<tr>
<td>2006 Jul 29–Aug 29</td>
<td>1</td>
<td>14.14</td>
<td>2.07</td>
<td>70.0</td>
<td>12.05</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>2008 May 12–Nov 1</td>
<td>2</td>
<td>8.06, 11.03</td>
<td>3.93, 2.11</td>
<td>37.1, 48.5</td>
<td>4.07, 8.92</td>
<td>1</td>
<td>4.74</td>
<td>1.07</td>
<td>65.5</td>
</tr>
<tr>
<td>2009 May 28–Nov 1</td>
<td>1</td>
<td>7.01</td>
<td>1.63</td>
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<td>3.87</td>
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<td>2</td>
<td>3.40, 4.33</td>
<td>1.25, 1.59</td>
<td>35.9, 33.2</td>
<td>2.20, 2.71</td>
<td>5</td>
<td>2.94–5.00</td>
<td>1.07–1.34</td>
<td>20.3–67.2</td>
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<tr>
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<td>2</td>
<td>3.41</td>
<td>0.58, 1.38</td>
<td>49.8, 32.2</td>
<td>2.40, 1.70</td>
<td>5</td>
<td>2.11–3.89</td>
<td>0.58–1.31</td>
<td>23.2–61.4</td>
</tr>
<tr>
<td>2012 Apr 28–Oct 14</td>
<td>1</td>
<td>5.29</td>
<td>0.90</td>
<td>53.8</td>
<td>4.15</td>
<td>2</td>
<td>1.74, 3.07</td>
<td>0.65</td>
<td>35.8, 55.6</td>
</tr>
</tbody>
</table>
3.2 The 2009–2012 campaigns

The source showed an X-ray flare with a nearly symmetrical profile in Period 4 (see Table 3) when the 0.3–10 keV flux increased by a factor of 4 in 21 d and then faded to its initial level in 18 d. The 0.1–300 GeV flux exhibited a fast flaring behaviour with a powerful short-term outburst by a factor of 11 whose peak coincides with the first XRT pointing, performed during the aforementioned flare. Note that the XRT observations are separated by the 1–2 week intervals and we cannot exclude the existence of fast outbursts, similar to those seen in the γ-ray band. The UVOT fluxes peak a week earlier than MJD = 55111, corresponding to the moment of the maximum X-ray flux (although we are not able to draw any firm conclusion about the length of a hard lag due to the sparsely sampled pointings). The K-band flux shows three consecutive short-term outbursts during the X-ray flare by a factor of 1.27–1.70. However, the highest infrared flux was by 35 per cent lower compared to that observed in 2009 May when PKS 2155–304 was pointed only twice by the XRT (on MJD = 54979).

The source exhibited a high-flux level in Period 5 (see Table 3) when the 0.3–10 keV light curve showed two maximum states, separated by a dip by 42 per cent in the flux (on MJD = 54363) and a similar behaviour was the case also in the UVOT bands. The LAT observations also showed a two-peak structure but a dip in the 0.1–300 GeV light curve was observed on MJD = 54367.

However, the LAT data from the previous three days are very poor, and we did not analyse them. Therefore, it is possible that the delay in the gamma-ray dip with respect to that in X-rays was shorter. In this period, the source showed a fast X-ray flare during the October campaign (MJD = 55473–5500) when the 0.3–10 keV flux increased by a factor of 2.6, and it showed a fast rise by 43 per cent in about 1.63 d, before reaching its maximum. An increasing γ-ray activity was also observed, with the consecutive two short-term outbursts whose peaks are separated by 7 d and the second one lags the X-ray peak by <1 d. Afterwards, we observe a more intensive gamma-ray flare by a factor of 2.8. Unfortunately, no XRT observations were carried out during this period. The UVOT light curves followed that from 0.3–10 keV energy band, although they showed significantly lower fractional amplitudes. Note that the K-band flux exhibited a decaying trend by a factor of 3 during the X-ray flare.

A significant X-ray variability occurred during Period 6 (see Table 3) when the beginning of the monitoring coincided with the epoch of a long-term flux decay in the source, superimposed by a very asymmetrical short-term outburst whose decay phase was three times longer compared to the brightening. During this period, the source was very active in the 0.1–300 GeV energy band and showed the three consecutive, very sharp peaks during the MJD = 55722–55736 period, whose corresponding fluxes were greater by a factor of 3, 2.15, and 2.41, respectively, compared to their initial levels. It seems, the source underwent another short-term X-ray outburst after MJD = 55750 when the 0.3–10 keV flux increased by 35 per cent. However, no XRT observations were performed during two weeks till MJD = 55771 when PKS 2155–304 faded to its historical minimum. Meanwhile, the source showed a strong gamma-ray outburst by a factor of ~6. The UVOT and K-band fluxes also exhibited a long-term decay in this period with short-term UV-optical brightenings without a lag with respect to X-rays. The source showed an increasing X-ray activity during the September–October campaign. In the epoch of the maximum X-ray flux, the LAT recorded two consecutive short-term flaring events with a flux increase by a factor of 5.8 and 5, respectively. The UVOT light curves basically followed the behaviour of that in the 0.3–10 keV band. However, the UV-optical fluxes were not the lowest on MJD = 55771, similar to that from 0.3–10 keV energy band.

Finally, the source showed a flaring activity in Period 7 (see Table 3) when the maximum 0.3–10 keV flux coincided with the peak of a short-term HE outburst. Afterwards, we observe a dip and subsequent outburst in both bands whose maximum flux moments are separated by a week. Unfortunately, no Fermi observations of PKS 2155–304 were performed during the interval MJD = 54194–54199, and we cannot exclude that the moment of the highest 0.1–300 GeV flux was earlier. The XRT observations have weekly separations in this epoch, and, therefore, no firm conclusion about the lag between these two bands can be made. The UVOT light curves show a correlated behaviour with that from the 0.3–10 keV energy band without an indication of a lag. A short-term X-ray outburst was also seen from the 2012 June observations with the highest X-ray flux on MJD = 56101.9. In the same period, the LAT flux increased by a factor of 4, attaining its maximum by about 3 d earlier. However, the LAT observations were very poor in these epochs and we had to use the 5 d bins, centred on the XRT pointings, to detect the source above the 3σ threshold. As for the infrared observations, the K-band light curve basically showed a flux increase and peaked by a week later compared to the X-ray one. Afterwards, it exhibits a long-term decay, similar to other spectral bands.

3.3 $F_{\text{var}}$ versus energy

According to Zhang et al. (2005), if the fractional rms variability amplitude of the source increases with photon energy, this may be an indication of a significant spectral variability. From the HESS observations of the prominent 2006 July flare in PKS 2155–304, Abramowski et al. (2010) reported a trend of increasing fractional amplitudes with higher frequencies when $F_{\text{var}}$ was related with a photon energy $E$ as

$$F_{\text{var}}(E) \propto E^m,$$

with $m = 0.19$ in the frequency interval $\log\nu = 25.82–26.44$ Hz. We constructed a scatter plot $\log F_{\text{var}}$ versus $\log\nu$ for this epoch in the presence of a much wider frequency range from the radio to the VHE parts of the spectrum ($\log\nu = 9.93–26.44$ Hz), including the values of $F_{\text{var}}$ from the aforementioned paper (see the first plot of Fig. 11). In that case, we obtained a slower increase of a fractional amplitude with energy ($m = 0.08$).

We have found similar trends also for the later multwavlength observations of PKS 2155–304. Namely, the trend $F_{\text{var}}(E) \propto E^m$ with $m = 0.12$ in the IR-HE part of the spectrum was the case during the flare, recorded in Period 4. A slower increase of the fractional amplitude with energy $F_{\text{var}}(E) \propto E^{0.06}$ is found for the epochs of two X-ray flares which occurred in Period 5 (see the previous section).

Equation (3) was also the case during the 2011 May–July (MJD = 55701–55771) observations but its slope is significantly lower compared to those from the previous years ($m = 0.02$ as for a short-term outburst as well for a whole period). The fractional amplitude exhibited the same functional dependence with a photon energy for the period MJD = 55808–55858 as it did during the Period 5 flares. Note that the source showed a very extreme brightening by 3.3 mag in 3 d in the K band (after MJD = 55850) while no significant variability is seen in the case other four SMARTS bands ($B, V, R, J$). Due to the chance that this event might be related to some instrumental effect, we have not included the $F_{\text{var}}$ value, corresponding to this band, in the aforementioned relationship. Finally, $F_{\text{var}}$ increased with energy as $\propto E^{0.05}$ in the epoch of X-ray flare, observed in Period 7.
3.4 Time-scales

The structure function (SF) analysis is a powerful tool for the derivation of flux variability time-scales, especially when the observations are distributed unevenly in time (see Rami, Wiita & Gupta 2009 for a detailed description of SF, its properties and methods of a variability time-scale extraction). The first row of Fig. 2 presents the SF plots from the XRT 2005–2012 observations, constructed via the 5 d bins (in a logarithmic representation), and 20 d bins (for a clarity of the SF behaviour at the longer time lags; in a linear representation), respectively. After the initial rise, the SF shows a break at $\tau^\text{max} = 30$ d indicating thus the presence of a flux variability on this time-scale. We observe the next clearly expressed maxima at $\tau^\text{max} = 100$ d, $\tau^\text{max} = 420$ d, $\tau^\text{max} = 820$ d, $\tau^\text{max} = 1200$ d, preceded by the minima at $\tau^\text{min} = 55$ d, $\tau^\text{min} = 300$ d, $\tau^\text{min} = 520$ d, $\tau^\text{min} = 940$ d. For the longer time lags, no clearly expressed maxima are seen. Using the method, adopted in Gaur et al. (2010), we have derived following time-scales: $t_1 = 30$ d, $t_2 = 45$ d ($t^\text{max} - t^\text{min}$), $t_3 = 120$ d ($t^\text{max} - t^\text{min}$), $t_4 = 300$ d ($t^\text{max} - t^\text{min}$), $t_5 = 260$ d ($t^\text{max} - t^\text{min}$).

According to Emmanoulopoulos, McHardy & Utley (2010), there may be spurious breaks in the SF, corresponding to no intrinsic timescales. One should therefore apply an alternative tool for a timescale derivation to verify the results obtained via the SF analysis. In the case of unevenly distributed observations, it is better to use the autocorrelation function (ACF) which is tolerant to the blank time intervals (Heidt & Wagner 1996). While the above-mentioned time-scales $t_1, t_2, t_3$ can be easily derived also with this method, we have not found any confirmation for the longer $t_4, t_5$ time-scales, and they may be simply related to seasonal gaps in the observations.

Fig. 2 also presents the SF plot corresponding to the Flare 2 of Period 3 (constructed with the 5 d bins, see the first panel in second row of Fig. 2). It shows two maxima at $\tau^\text{max} = 50$ d and $\tau^\text{max} = 90$ d, separated by the minimum at $\tau^\text{min} = 70$ d. Hence, we obtain the nominal variability time-scales of 50 d and 20 d ($t^\text{max} - t^\text{min}$), according to the method of a time-scale derivation described in Gaur et al. 2010) which should be related to the flux decay and increase events during Flare 2, respectively. For the Period 7 flare, the SF shows the breaks at $\tau = 40$ d and $\tau = 120$ d (the middle panel of the second row in Fig. 2) which reveals a longer time-scale flaring event superimposed by that of shorter duration.

3.5 Intra-day variability

We have also performed an intensive search for an intra-day X-ray variability in PKS 2155–304 (IDV, i.e. a flux change within a day; see Wagner & Witzel 1995). For this purpose, we constructed the 60 s binned light curves and used the variability indicator introduced by Kesteven, Bridle & Brandie (1976). For the observation with the fluxes $F_i$ ($i = 1, \ldots, N$), each with the standard error $\sigma_i$, we compute the quantity

$$X^2 = \sum_{i=1}^{N} \frac{(F_i - \langle F \rangle)^2}{\sigma_i^2}.$$  (4)

In the case of purely random errors, $X^2$ should be distributed as $\chi^2$ with $N - 1$ degrees of freedom. We consider the source to be variable if the probability $P(X^2)$ of exceeding the observed $X^2$ by chance is <0.1 per cent, and it is classified as non-variable if the probability is >0.5 per cent (see Andruchov, Romero & Cellone 2005).

We provide a summary of the intra-day flux variabilities detected at the 99.9 per cent confidence in Table 4. During the 2011 July 15 observation (MJD = 55757; first and second plots in Fig. 3), the source showed a very fast flaring event corresponding to the first orbit out of two during this pointing. Both the SF and the ACF analysis show a time-scale of about 400 s. The light curve exhibits an almost symmetrical profile (skewness $g = 0.06$) for this event where the decaying part lasts about 400 s and there is a much slower decrease in the flux during last three bins, hinting on the end of this non-stationary event. It is represented well with a Gaussian fit as follows

$$F = 1.92e^{-(t-246.5/391.6)^2} + 0.89e^{-(t-485/255.6)^2},$$  (5)

For the X-ray IDVs, described in this section, the corresponding light curves and SF plots are provided in Figs 3 and 2, respectively.
Figure 3. Light curves from the observations with IDVs (extract). The dashed line in the second figure represents a Gaussian fit to the data.

where \( t \) is the time (in seconds) since the exposure start. We therefore suggest that the flux increase time should be as long as the aforementioned decay time. The flux doubling time \( T_2 \sim 600 \text{ s} \) defined as (Edelson 1992)

\[
T_2 = \left| \frac{\Delta t}{\Delta \ln F} \right|
\]

The fractional amplitude \( F_{\text{var}} = 15.8 \text{ per cent} \) for this event which seems to be the part of a longer intra-day variability – the source shows the lower flux \( (F_{0.3–10\text{keV}} = 0.74 \text{ cts s}^{-1}) \) from the second orbit, separated from the first one by 22.5 ks. Totally, we have \( F_{\text{var}} = 30 \text{ per cent} \) for this observation.

A significant IDV was observed on 2008 September 5 (see Section 3 for the corresponding MJD) when two different pointings with 29.5 ks and 6 ks durations were performed within the 70 ks interval. The first observation consists of the six orbits, separated by the 4–5.9 ks intervals. We had therefore to use the 2 ks bins when constructing the corresponding SF while there are spurious periodic dipps in the SF for the smaller bins. This pointing shows a gradual increase in the orbit-binned flux by 32 per cent to 12.22 cts s\(^{-1}\), and the second one includes only two orbits exhibiting a gradual decrease in the flux down to 7.15 cts s\(^{-1}\). The SF, constructed for both pointings, shows a break at \( \tau = 40 \text{ ks} \) which may be accepted as a time-scale of this fast event (confirmed also by the ACF analysis). On 2009 May 28 (MJD = 54979), the flux initially increased by 4.5 per cent in ~5 ks and then decayed gradually 1.43 times in about 35 ks, followed by an increase by 13.2 per cent in 6 ks. The corresponding SF shows a maximum at \( \tau = 38 \text{ ks} \). PKS 2155–304 was also variable on 2010 April 29 (MJD = 55315) – it increased by 37.5 per cent in 23 ks, followed by a slow decay till the end of the pointing. The time-scale of this event \( t_{\text{var}} = 26 \text{ ks} \), corresponding to the peak of the SF (the last panel of the third row of Fig. 2). No smaller time-scale fluctuations were detected within each orbit.

The source showed a very interesting behaviour during the 2007 April 22 pointing (MJD = 54212) – it weakened by a factor of 1.28 between the first two consecutive orbits (\( \Delta \tau \sim 5.7 \text{ ks} \)), and then it did not exhibit a significant variability during ~28 ks interval with respect to the 5.2 cts s\(^{-1}\) level and began to rise from the Orbit 7 with 20 per cent till the end of the observation. The corresponding SF exhibits two maxima at \( \tau_{\text{max}}^1 = 21 \text{ ks} \) and \( \tau_{\text{max}}^2 = 36 \text{ ks} \), separated by a minimum at \( \tau_{\text{min}}^1 = 27 \text{ ks} \). We have therefore two nominal variability time-scales of 21 ks and 9 ks, corresponding to the rising and decaying parts of the light curve, respectively. The fractional amplitude is 11.0 per cent during the flux decay, and it equals 9.4 per cent in the case of a flux increase. The source was also variable during the three close observations, performed within 16.7 h on 2008 May 12–13 (MJD = 55598.63–55599.13). It showed brightenings with 11–28 per cent in the course of 6–17 ks, followed by the decays with the fastest flux change by a factor of 1.2 in ~4.7 ks. The corresponding SF shows the time-scales of ~12 ks (two maxima at \( \tau_{\text{max}}^1 = 12 \text{ ks} \) and \( \tau_{\text{max}}^2 = 36 \text{ ks} \), separated by a minimum situated at \( \tau_{\text{min}}^1 = 24 \text{ ks} \)).

The 2012 April 28 observation corresponds to the source’s faint state with the average flux of 0.90 cts s\(^{-1}\) (MJD = 56045). In the case of 60s bins, the source is qualified as a possible variable one (\( \chi^2 = 1.328 \) with 217 d.o.f.) but we obtained a clear IDV with \( \chi^2 = 2.375 \) (d.o.f. = 42) from the light curve constructed via the 300 s binned fluxes. The flux increased by 10 per cent in ~28 ks followed by a decay by a factor of 1.2 in about 17.5 ks.

We also revealed eight more IDVs but the corresponding observations do not have enough time coverage to derive the variability time-scales. The most notable event corresponds to the 2006 April 16 pointing which consists of 15 very short (0.2–0.24 ks) orbits separated by the 5–5.8 ks intervals (5.7 ks of total exposure; MJD = 53841). For the bins shorter than 5 ks, the SF exhibits spurious dips, and it does not show clearly expressed breaks for the larger bins. The source showed a flux increase by about 50 per cent during the short pointing of 2011 October 9 (MJD = 55843; \( \Delta t = 764 \text{ s} \)) with \( F_2 < 2 \text{ ks} \). It seems this change is superimposed by two very fast fluctuations; however, they are only of the (1–2)\( \sigma \) confidence.

Note that the source also showed IDVs from the HESS 2006 August 2 and 5 observations with fractional amplitudes of 10.2 and 22.6 per cent, respectively (MJD = 53949–53952; see the last panel of Fig. 3). In the first case, the source showed fluctuations with time-scales of 3.5–4 ks. We observe an IDV also from the contemporaneous XRT observations – there are two short pointings separated by 22 h interval and, therefore, we had no possibility to study an inter-band correlation.

Our timing study of long-term XRT observations of PKS 2155–304 shows that the source was highly variable both on longer (weeks-to-months) and intra-day time-scales. During the longer-term flares and short-term outbursts, the 0.3–10 keV fluxes varied by a factor of 2–7, and the IDVs are characterized by fractional variability amplitudes of 7.5–30 per cent. The X-ray flux variability exhibited an erratic character in this source and no signatures of periodic variations are revealed.
Table 5. Extract from the summary of the XRT spectral analysis with logparabolic model. The $E_p$ values are given in keV; de-absorbed 2–10 keV and 0.3–10 keV fluxes (Columns 6 and 7) in units of $10^{-11}$ erg cm$^{-2}$ s$^{-1}$.

<table>
<thead>
<tr>
<th>ObsID</th>
<th>$a$</th>
<th>$b$</th>
<th>$K$</th>
<th>$E_p$</th>
<th>2–10 keV flux</th>
<th>0.3–10 keV flux</th>
<th>HR</th>
<th>$\chi^2$/d.o.f.</th>
</tr>
</thead>
<tbody>
<tr>
<td>00030527003</td>
<td>2.40(0.06)</td>
<td>0.02(0.001)</td>
<td>0.02(0.001)</td>
<td>2.32</td>
<td>9.15</td>
<td>0.340</td>
<td>1.018/164</td>
<td></td>
</tr>
<tr>
<td>00030795001</td>
<td>2.40(0.01)</td>
<td>0.02(0.001)</td>
<td>0.02(0.001)</td>
<td>2.32</td>
<td>9.15</td>
<td>0.340</td>
<td>1.018/164</td>
<td></td>
</tr>
<tr>
<td>00030795003 orb1</td>
<td>2.60(0.02)</td>
<td>0.02(0.001)</td>
<td>0.02(0.001)</td>
<td>2.32</td>
<td>9.15</td>
<td>0.340</td>
<td>1.018/164</td>
<td></td>
</tr>
<tr>
<td>00030795003 orb2</td>
<td>2.50(0.02)</td>
<td>0.02(0.001)</td>
<td>0.02(0.001)</td>
<td>2.32</td>
<td>9.15</td>
<td>0.340</td>
<td>1.018/164</td>
<td></td>
</tr>
</tbody>
</table>

Figure 4. Distribution of the values of different spectral parameters: photon index at 1 keV, HR and curvature parameter. The dashed lines represent the lognormal fit to the distributions.

4 X-RAY SPECTROSCOPY

Spectral analysis was performed by fixing the absorbing column density $N_{HI}$ to the Galactic value (see below) and using the following two spectral models: (a) simple power-law (Takahashi et al. 1996)

$$F(E) = KE^{-\Gamma},$$

where the units of the normalization constant $K$ are photons cm$^{-2}$ s$^{-1}$ keV$^{-1}$, $E$ is the photon energy (in keV), $\Gamma$ the photon index throughout the observation band; (b) logparabolic model (M04)

$$F(E) = K(E/E_1)^{-\alpha + b\log(E/E_1)},$$

with $E_1$ the reference energy, generally fixed to 1 keV; $a$ the photon index at the energy $E_1$; $b$ the curvature parameter. The values of $K$, $a$, $b$ parameters are derived during the fit process. The location of the SED peak is given by

$$E_p = E_110^{2a-2b}.$$

We fixed the equivalent hydrogen column density to the weighted mean value $N_{HI} = 1.48 \times 10^{20}$ cm$^{-2}$, derived via the Total Galactic HI Column Density Calculator$^g$ on the basis of Leiden/Argentine/Bonn (LAB) Survey$^h$ of Galactic HI (Kalberla et al. 2005).

$^7$The corresponding errors are calculated by propagating those of a and b parameters, according to the recipe in Bevington & Robinson (2002).

$^8$http://heasarc.gsfc.nasa.gov/cgi-bin/Tools/w3nh/w3nh.pl

$^9$Generally, the spectra of PKS 2155–304 fitted better with the models for this value of $N_{HI}$ compared to $N_{HI} = 1.69 \times 10^{20}$ cm$^{-2}$ (derived on the basis ofDickey & Lockman 1990) or $N_{HI} = 1.36 \times 10^{20}$ cm$^{-2}$ (based on Lockman & Savage 1995) which were used by some authors in the case of XMM–Newton, Chandra and Swift–XRT observations (see A09, Zhang 2008; Tramacere, Massaro & Cavaliere 2007a).

For each spectrum, the model validity was checked by means of reduced chi-square, distribution of the residuals, and F-test. We restricted our analysis to the spectra whose PHA bins were more than 40. In the opposite case, there are high uncertainties related to the values of spectral parameters (especially for the logparabolic model). Generally, the source showed curved spectra – the power law was excluded at 99.99 per cent significance or the logparabolic model was clearly preferred by the aforementioned tests. The vast majority of the curvatures are detected at the 3$\sigma$ confidence. However, we have also included those detected at the 2$\sigma$ and even above 1$\sigma$ confidence in Table 5 when the power law was rejected by the tests (although the latter are not used for a construction of the distribution of this parameter in Fig. 4). However, it was impossible to make conclusions about the preference of any model for several spectra. They belong to the epochs when the UV-optical fluxes were significantly higher compared to those from the 0.3–10 keV energy band. Therefore, the peak of synchrotron SED is shifted far from the instrumental range of the XRT that, on its turn, makes it difficult to evaluate a possible curvature, and the simple power-law model gives relatively better description of the spectrum (see M08). However, the X-ray flux was greater compared to those from the UVOT bands in the case of the pointing with ObsID = 00030795029 where the power law gives a better statistics compared to that obtained with the logparabolic fit, although the latter cannot be excluded at 99.99 per cent significance. For these spectra, $\Gamma = 2.40–2.72$, and $F_{0.3–10 keV} = (0.55–3.25) \times 10^{-10}$ cgs (hereafter cgs stands for erg cm$^{-2}$ s$^{-1}$).

The results of the spectral analysis, performed with the logparabolic model, are provided in Table 5. The HR values...
Table 6. Distribution of the different spectral parameters: minimum and maximum values (Columns 2 and 3, respectively), distribution peak (Column 4) and variance (last column).

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Min.</th>
<th>Max.</th>
<th>Peak</th>
<th>( \sigma^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a )</td>
<td>2.05</td>
<td>2.75</td>
<td>2.45</td>
<td>0.023</td>
</tr>
<tr>
<td>( HR )</td>
<td>0.145</td>
<td>0.543</td>
<td>0.27</td>
<td>0.0081</td>
</tr>
<tr>
<td>( b )</td>
<td>0.13</td>
<td>0.80</td>
<td>0.37</td>
<td>0.018</td>
</tr>
</tbody>
</table>

calculated as the ratios of de-absorbed 2–10 keV to 0.3–2 keV fluxes. In Table 6, we present the properties of the distribution of the \( a \), \( HR \), \( b \), \( E_p \) parameters. The distribution peaks are derived via the lognormal fit to the corresponding histograms. The photon index shows a wide range of the values with \( \Delta a = 0.70 \) (see Fig. 4, first plot) whose 65 per cent out of these values are included in the interval (2.40, 2.60). The first plot of Fig. 5 shows a moderate, statistically significant anticorrelation between \( a \) and 0.3–10 keV model flux (see Table 7 for the Pearson correlation coefficient and corresponding \( p \)-value). This result reveals that the source mainly followed a ‘harder-when-brighter’ trend which is more evident if we construct a scatter plot for photon index and 2–10 keV flux – there is a stronger anticorrelation with \( r = -0.73 \). Note that the hardest spectrum corresponds to a high brightness state in the source \( (F_{0.3-10 keV} = 7.01 \text{ cts s}^{-1} \text{ m}^{-2} \text{ keV}^{-1} \text{ sr}^{-1}) \) and the maximum flux recorded during the Period 4 flare, and the softest spectrum is found in the case of the pointing with ObsID = 30795097 which shows \( F_{0.3-10 keV} = 2.73 \text{ cts s}^{-1} \text{ m}^{-2} \text{ keV}^{-1} \text{ sr}^{-1} \). However, a significant scatter of data points with respect to the linear fit gives an evidence that this trend was not always the case. A pure CW evolution occurred during the flares of 2006 April (MJD = 53836–53855), 2008 August–October (Flare 2), 2009 September–November (Period 4), 2011 September–October (55808–55858) while the source showed an opposite trend during the 2010 October (55473–55500; see Fig. 6 for the HR–flux planes for these events). A ‘harder-when-brighter’ evolution was dominant during the 2006 July–August (Period 2), 2012 June–August (MJD = 56680–56108) observations and the changes to an opposite trend were mainly associated with the short-term outbursts, superimposed on the longer variable event. In the case of IDVs, the \( a \) parameter showed a variability at the 3\( \sigma \) and 2\( \sigma \) confidence levels. We basically observe a ‘harder-when-brighter’ trends here. However, changes to an opposite trend are also presented, similar to the longer-term events.

The second plot of Fig. 4 presents the distribution of HRs. The maximum value of HR is derived from the spectrum extracted from the sixth orbit of the pointing with ObsID = 00030795040. Although the corresponding value of \( a \) parameter (2.16) also shows a hard spectrum, but it is not the lowest. We checked the spectrum for a flattening in the 4–10 keV energy range, reported in Zhang (2008) for PKS 2155–304 from the XMM–Newton observations performed on 2006 May 1 and November 7. However, we have not found a similar trend of increasing residuals with energy for the aforementioned spectrum (as well for those from other orbits which are also the hardest among all XRT observations with HR = 0.492–0.532).

We have also obtained a wide range of the spectral curvature \( (\Delta b = 0.67) \), the third plot of Fig. 4 which shows a moderate negative correlation with the 0.3–10 keV model flux (see the third panel of Fig. 5). From Fig. 7, we see that the \( b \) parameter followed a trend opposite to the flux evolution during the major part of 2006 July–August, 2008 August–October, 2011 June–July, 2011 September–October flares. A similar situation was during the 2008 September 5 \( (b = 0.20–0.54) \) and 2009 May 28 \( (b = 0.29–0.52) \) IDVs. The curvature parameter also shows a negative, although a weaker correlation \( (r = -0.46) \) with the HR (fourth panel of Fig. 5). We have not found a significant correlation with the \( a \) parameter \( (r = 0.10, p = 0.22) \) in contrast to that reported in M04 from the 13 BeppoSAX observations of Mrk 421.

The \( E_p \) values, derived from the XRT spectra of PKS 2155–304 via equation (9), range between 0.02 and 0.89 keV. However, their vast majority are detected below the 3\( \sigma \) significance and they generally are systematically higher compared to those obtained from the broad-band SEDs (using equation 20 or equation 21). Therefore, the \( E_p \) values from the X-ray spectral analysis should be considered as upper limits to the intrinsic ones.\(^{11}\) The contemporaneous optical–UV fluxes are comparable and sometimes even higher than the de-absorbed 0.3–2 keV and 2–10 keV fluxes, i.e. the intrinsic position of the synchrotron SED peak is poorly constrained by the XRT observations.

The curved spectra were also examined with the alternative form of the logparabolic model (M08)

\[
F(E) = S_p 10^{-b \log^2(E/E_p)},
\]

with \( S_p \) the SED peak height. It is very useful since the correlation between \( E_p \) and \( S_p \) in the power-law form can provide an indication about the driver of the observed spectral changes in the framework of the synchrotron emission mechanism from one dominant homogenous component (see T09). However, this form gives unacceptable values of the \( E_p \) parameter of 1.55–2.35 keV for PKS 2155–304 while the broad-band SEDs constructed on the basis of the XRT, UVOT and the other available radio-optical data show the presence of a SED peak below 1 keV (see Section 6). This systematic shift is due to the fact that \( E_p \) is close to the edge or below the detector spectral window (A. Tramacere, private communication). Note that the (8) form was always preferred by the F-test and it yielded \( E_p \) values (calculated via equation (9)) close to those derived from the broad-band SEDs. Therefore, we used it for our analysis.

On the other hand, the errors associated with the \( E_p \) values from the broad-band SEDs can be as high as 0.5 for \( \log v_p \) (defined as \( v_p = E_p/h \)) when we do not have simultaneous radio observations (which is the case for most XRT observations of our target) or the UVOT performed its observation only in one band out of six along with that of XRT (P. Giommi, private communication). Consequently, we cannot construct the distribution of this parameter or draw firm conclusions about its time variability.

Our spectral study shows that the X-ray spectra of PKS 2155–304 are mainly curved with broad ranges of photon index, curvature parameter and HR which exhibit significant variability with the flux at different time-scales. The source mainly showed a harder-when-brighter evolution in a HR–flux plane although an opposite trend was also observed. However, we cannot firmly constrain the range of \( E_p \) parameter and study its evolution with the flux since the lower-energy peak of the SED is situated close the edge or below the XRT spectral window.

\(^{11}\) Indeed, we can only consider a peak as ‘detected’ when one has experimental data at energies both below and above \( E_p \). That is not the case for most observations of PKS 2155–304.
5 INTER-BAND CROSS-CORRELATIONS

The soft (0.3–2 keV) and hard (2–10 keV) X-ray fluxes from the 2005–2012 observations are plotted versus time in Fig. 8. The former varied between $1.69 \times 10^{-11}$ cgs and $2.57 \times 10^{-10}$ cgs. In the case of hard X-ray flux, we have $F_{\text{max}}^{\text{H}} = 3.6 \times 10^{-12}$ cgs while $F_{\text{H}} = 1.14 \times 10^{-10}$ cgs. In fact, these ranges may be larger since the spectra from the pointings with ObsID 30795080–30795083 (when the source showed its lowest historical state) are poor and we have not analysed them. Note that the higher 2–10 keV flux of $1.51 \times 10^{-10}$ cgs was obtained from the BeppoSAX 1997 November observations of our target (Z02).

We see that these fluxes basically show a highly correlated behaviour. This is also evident from the second plot of the upper row in Fig. 8 where the 2–10 keV fluxes are plotted versus those from the 0.3–2 keV energy band. There is a strong correlation with $r = 0.90$ between these quantities. However, they were not always correlated. For example, the hard flux decayed 1.4-times between MJD = 56108 and MJD = 56135 while the source showed a brightening with 23 per cent in the 0.3–2 keV energy band. The scatter of the data points with respect to a linear fit increases with the energy.

We have searched for the inter-band lags between the orbit-binned 0.3–2 keV and 2–10 keV fluxes for the IDVs from the deep XRT observations with IDVs. These fluxes are plotted versus time in the middle row of Fig. 8 and the last row contains the corresponding discrete correlation functions (DCF), defined for each time lag $\tau$ as (Hufnagel & Bregman 1992)

$$ DCF(\tau) = \frac{1}{M} \sum_{i,j} UCDF(i,j)(\tau), $$

where the set of unbinned discrete correlations between the $a$ and $b$ time series is given by

$$ UCDF(i,j) = \frac{(a_i - \bar{a})(b_j - \bar{b})}{\sqrt{\sigma_a^2 \sigma_b^2}}. $$

Here, $a_i$ and $b_j$ are the points of the $a$ and $b$ sets, respectively; $\bar{a}$ and $\bar{b}$ their mean values; $\sigma_a^2$ and $\sigma_b^2$ the variance of each set; $M$ number of pairs for the given time lag. Since we observe its maximum practically at $\tau = 0$ for the 2008 September 5 event, there is no significant soft lag, it does not exceed 1 ks. A similar result is obtained for the 2009 May 28 event. However, a soft lag with $\tau \approx 7$ ks is evident from the plot constructed for the 2010 April 29 observation (derived via the polynomial fit to the DCF. Nevertheless, the same result has been obtained by the lognormal fit to the central part of the DCF). It also shows secondary peaks at $\tau \sim \pm 40$ ks which generally are related to the finite length to the data streams and do not show any intrinsic time shift between them (see Hufnagel & Bregman 1992).

The 0.3–10 keV model flux exhibits a correlation with those from the 0.1–300 GeV energy with $r = 0.63$. We have examined the dependence of X-ray and $\gamma$-ray fluxes in the form $F_{\gamma} \propto F_{\text{H}}$ (see the first panel of Fig. 9). However, this result is not directly comparable with those reported by A09 since the latter were obtained for the VHE $\gamma$-ray band. Generally, the daily binned LAT fluxes are related to those from the 0.3–10 keV energy band more than linearly. We observe $\eta \geq 2$ in a few cases which do not show a tendency to any flare and they may be related to the time lag between the flux variabilities in these bands (see the discussion in Section 6.2).

In Section 3, we have reported a correlation between the VHE and 0.3–10 keV fluxes in the period MJD = 53948–53977 (following the VHE flare of 2006 July between MJD = 53944 and MJD = 53946, studied by A09 and Abramowski et al. 2012). The majority of the XRT spectra from this period are very poor and the derivation of de-absorbed model fluxes from them may lead to large uncertainties. Therefore, we constructed a scatter plot in the cts s$^{-1}$ (0.3–10 keV fluxes) versus erg cm$^{-2}$ s$^{-1}$ (VHE fluxes, from Abramowski et al. 2012 and A09) representation (second panel of Fig. 9) that shows a strong positive correlation with $r = 0.86$.

Due to this reason, we could not check the relation $F_{\gamma} \propto F_{\text{H}}$ for the whole period. However, we analysed the spectra for the sub-period
The 0.3–10 keV band behaviour of PKS 2155–304

Figure 6. HR–total flux planes corresponding to the different long-term flares (extract).

Figure 7. De-absorbed 0.3–10 keV flux (divided by their minimum or mean values during the given period) and curvature parameter, plotted versus time for different long-term flares and IDVs (extract).

MJD = 53648–53653 which showed that the VHE fluxes varied only linearly with X-ray fluxes during these days, in contrast to the MJD = 53945–53946 period when the cubic relation between VHE and X-ray flux variations was found by A09.

The XRT fluxes show a strong correlation with those from the UVOT bands ($r = 0.73–0.76$; see the third panel of Fig. 9 where the 0.3–10 keV and UVW2-band fluxes are plotted in the cgs units). They exhibit a relatively weak correlation ($r = 0.63$) with the B-band fluxes. We have also found a correlation between the UVOT and the 0.1–300 GeV fluxes with $r = 0.58 – 0.66$ (see Table 7 and the last panel of Fig. 9 where the UVW2-band fluxes are plotted versus those from the LAT band). As for the IR observations, a moderate correlation is evident between the 0.3–10 keV and J-band fluxes while no significant correlation is found between the XRT and K-band fluxes ($r = 0.31, p = 0.06$).

Our study of multiwavelength cross-correlations has revealed that the one-zone SSC scenario seems to be valid for the most optical-to-γ-ray flares observed during 2006–2012 in PKS 2155–304. However, the available IR and radio data show that the source’s behaviour in the lowest-energy part of the spectrum mostly was not correlated with that in the higher-energy domain that could be related to the generation of radio-IR emission in the blazar regions which are different from that responsible for the optical-γ-ray energy budget. Furthermore, the existence of different electron populations can be suggested from the ‘orphan’ X-ray flare with no counterpart in other spectral bands. The LAT observations also revealed some short-term outbursts without optical–X-ray counterparts. However, we cannot draw firm conclusions from these cases due to sparsely sampled Swift observations in the corresponding epochs.

6 DISCUSSION

6.1 Variability time-scales

Our timing analysis of the long-term XRT observations of PKS 2155–304 has revealed a number of the 0.3–10 keV flux variability events from sub-hour fluctuations to long-term flares with time-scales up to four months. The duty cycle (DC; i.e. the fraction of total observation time during which the object displays a variability) of IDVs is 48 per cent.

From previous studies, the fastest X-ray flux variability with a time-scale of $\sim 0.3$ h was reported by Edelson et al. (2001) for this source. However, we have found faster sub-hour variability from the 2011 July 15 observation with $t_{\text{var}} \approx 400$ s. The 0.5–5 keV light curve, provided in A09 (from the Chandra observation), shows a decay with time-scale $t_{\text{var}} \sim 400$ s just after the maximum flux, followed by the fluctuations of 1.7–7 ks. If we assume that these very fast events are triggered by the interaction between jet inhomogeneities (with higher density and stronger magnetic field) and relativistic shock wave, propagating downstream the jet (see e.g. Sokolov, Marscher & McHardy 2004), it is possible to evaluate the upper limit to the size of these inhomogeneities using the relation (T09)

$$R < \frac{c t_{\text{var}} \delta}{1 + z},$$

where $\delta$ is the Doppler factor of the emission zone producing this variable flux. Adopting $\delta = 29.6–56.8$ [calculated with the values of the $\Gamma, \theta$ parameters from Celotti & Ghisellini (2008) as

Figure 8. Cross-correlation between the soft (0.3–2 keV) and hard (2–10 keV) fluxes. The first figure shows a variability of these fluxes with time during 2005–2012, and the correlation between them is shown in the second panel of the upper row. In the second row, the evolution of hard and soft fluxes with time is shown for the different pointings (exhibiting IDVs). The corresponding DCF plots are provided in the last row. The dashed lines represent a polynomial fit to the DCFs.

Figure 9. Correlations between the fluxes from different spectral bands. The dashed lines in the first panel show different slopes of the relationship $F_\gamma \propto F_\eta^\delta$, while they stand for the linear fits to the scatter plots in other panels.

$\delta = 1/\Gamma(1 - \beta \cos \theta)$, or taken from Ghisellini & Tavecchio (2008), used to model the SEDs of PKS 2155−304 in this epoch. We obtain $R < 6 \times 10^{14}$ cm for the jet blob radius (i.e. an inhomogeneity passed by a shock front) producing VHE and X-ray emissions that vary on time-scales of 340–400 s. Note that the minimum timescale $t_{\text{var}} = 330 \pm 40$ s, obtained by Aharonian et al. (2007) from the fastest VHE flux doubling time $T_2 = 223 \pm 40$ s via the Fourier transform, can be used to evaluate the central black hole (BH) mass as (Liang & Liu 2003)

$$t_{\text{min}} \geq 0.98 \times 10^{-3} M_{\text{BH}}/M_\odot \text{ (s)}$$

that yields $M_{\text{BH}} \leq (3.4 \pm 0.4) \times 10^7 M_\odot$. This estimate is close to that obtained by Gaur et al. (2010) from the possible detection of a quasi-periodical oscillation in PKS 2155−304 (from the
XMM–Newton observation of 2002 May 24 with the period of ∼5.9 ks \( M(b;ν) = 7.4 \times 10^7 M_⊙ \), based on the assumption of a rapidly rotating BH (although the significance of this detection was below the 3\( σ \) threshold).

The earlier HESS campaign (2002–2003 period) also showed an extreme IDV with the increase by a factor of 2.7 in the VHE flux with \( τ_{\text{rad}} \sim 0.5 \) h, followed by a decay by a factor of 2.3 in a similar time. In the same epoch, an increase of the 2–10 keV flux by 60 per cent during the 1.5 ks interval was found by Aharonian et al. (2005). Among other X-ray campaigns, the extreme events were reported by Morini et al. (1986) – an increase of the 1–6 keV flux by a factor of 4 in 4 h, and by Sembay et al. (1993) – the 1.7–5.8 keV flux halved within 4 h.

### 6.2 Inter-band correlations

From the previous multiwavelength studies, PKS 2155−304 mainly showed a correlated variability in the different energy bands. The X-ray and VHE fluxes were strongly correlated, with no evidence of lags during the 2006 July flare which was the most intensively observed in different spectral bands (A09). The soft lags between the X-ray an UV fluxes, ranging between \( τ_{\text{soft}} < 3 \) h and \( τ_{\text{soft}} = 2 \) d were reported by Brinkmann et al. (1994) and Kataoka et al. (2000). No significant lags (\( τ_{\text{soft}} < 1 \) h) between the 3.5–10 keV and 0.1–1.5 keV energy bands were found by Z02. A possible hard lag between the 0.2–0.8 keV and 2.4–10 keV fluxes was reported by Zhang et al. (2006). Osterman et al. (2007) provided a very important result – the correlation between X-ray and UV/optical variability was the strongest and the time lag the shortest in the maximum brightness epoch of PKS 2155−304. The correlation weakened and the time lag increased to several days as the source became fainter. Similar results were reported by Zhang et al. (2006) for the light curves from the different X-ray bands during the 3-yr-long XMM–Newton observations; they showed a stronger correlation for the flaring states than those from the lower flux levels. Our results from the intra-day cross-correlation study of the 0.3–2 keV and 2–10 keV fluxes are in agreement with this scenario: the soft lag of \( ∼7 \) ks belongs to the epoch of a lower brightness state in the source (\( F_{0.3–10\text{keV}} ∼ 2.5 \) cts s\(^−1\)) while the lag \( τ_{\text{soft}} < 1 \) ks was derived for the states with higher fluxes (\( F_{0.3–10\text{keV}} ∼ 4–12 \) cts s\(^−1\)).

A detection of soft/hard lags allows us to evaluate different physical parameters in the jet blob, producing a variable emission. According to Zhang et al. (2006), the physical parameters of emitting zone – \( B \) (magnetic field strength) and \( δ \) – are related to the soft lag \( τ_{\text{soft}} \) (in seconds) as

\[
B^{3/2} = 209.91 \left( \frac{1 + z}{E_1} \right)^{1/3} \left[ \frac{1 - (E_1/E_2)^{1/2}}{τ_{\text{soft}}} \right]^{2/3} G, \tag{15}
\]

where \( E_1 \) and \( E_2 \) stand for the low and high energies (in keV) at which the observations are performed, respectively. Adopting \( E_1 = 1.1 \) keV and \( E_2 = 6 \) keV for the 0.3–2 keV and 2–10 keV energy bands,\(^{12}\) we obtain \( B^{3/2} \approx 0.13 \) G for the 2010 April 29 IDV (\( τ_{\text{soft}} = 7000 \) s). In order for the corresponding emission region to have a Doppler factor greater than 2 (generally used for a modelling of BLL SEDs), the strength of its magnetic field should satisfy the condition \( B \lesssim 0.1 \) G.

On the time-scales of days or longer, the spectral evolution mainly carried a ‘harder-when-brighter’ character (i.e. there was a possible soft lag) although an opposite trend is evident in the case of the 2010 October flare. A more complex evolution with sub-loops of opposite direction is seen in some cases which are mainly related to the short-term outbursts superimposed on the larger time-scale variability. Due to sparse sampling in the XRT and UVOT observations, we had not a possibility to construct DCFs and derive the values of soft/hard lag on the time-scales of days. However, a clear exception is the 2010 August–October flare which was not accompanied by those in other spectra bands – the fluxes from UV/optical bands show a decaying trend in this period and those from the HE and VHE γ-ray bands are the lowest in the maximum X-ray brightness epoch. This event is a challenge to the one-zone SSC model and may be related with the different electron population, producing an X-ray flare without significant contributions in other spectral bands. Note that Aharonian et al. (2005) did not find a correlation between the X-ray and γ-ray fluxes, or of any of the other bands during the 2002–2003 multiwavelength observations of PKS 2155–304.

A very fast X-ray flare, lasting only \( ∼20 \) min, was reported by Blazevjowski et al. (2005) in Mrk 421 from the PCA observation while no higher-energy counterpart was detected.

Similar to PKS 2155–304, a complex evolution in the HR–flux plane has been reported also for other HBLs. For example, during three flares out of five, observed by the XRT during 2006 April–July, the CW and CCW trends changed each other while a CCW loop was observed for the rest two flares (T09). The CW loops were detected for the same source by Takahashi et al. (1996) from the ASCA observations. Both types of the loops were also reported by Cui (2004) for the flares observed by the ASM. The CCW loops were found for H1426+428 by Falcone, Cui & Finley (2004).

The XRT observations of PKS 2155−304 revealed a broad range of photon index at 1 keV which exhibits an anticorrelation with the 0.3–10 keV flux, confirming the dominance of a ‘harder-when-brighter’ behaviour in this source. The same range \( a = 0.04–2.79 \) was reported in M08 (XMM–Newton observations). Note that our target generally had softer spectra compared to some other HBLs which also showed a wide range of this parameter: Mrk 421 (\( a = 1.61–2.54 \)), Mrk 501 (1.41–2.22), PKS 0548−322 (1.53–2.40), H1426+428 (1.68–2.22), IES 1959+650 (1.72–2.09) (M04; M08; Tramacere et al. 2007a; T09).

### 6.3 Spectral curvature

Our study shows that the spectra of PKS 2155−304 from the XRT observations are mainly curved. They are described well by a log-parabolic model with a broad range of curvature (\( b = 0.13–0.80 \)) which is significantly larger compared to that reported in M08 (\( b = 0.11–0.49 \)). Generally, the spectral curvature was found to be inherent to HBLs. The detailed study of the Mrk 421 observations, performed by ASCA, BeppoSAX, RXTE, and XMM–Newton missions during the 9 yr period, revealed the power law not to be adequate to describe a spectral shape – it mostly gave unacceptable values for \( χ^2 \) (higher than 1.5). In a few cases where \( χ^2 \) was acceptable, the residuals showed systematic deviations, clearly indicating the presence of a curvature (Tramacere et al. 2007a). Perlmutter et al. (2005) inspected the reasonability of the idea that the spectral curvature was the result of additional absorbing material in the HBL hosts but no positive results were obtained. Even leaving the low-energy absorption as a free parameter by M08, the power law was not adequate to describe the high-energy end of the X-ray spectra. The spectra obtained with different missions show a wide range of this parameter also for Mrk 421 (0.07–0.48), Mrk 501 (0.12–0.33), PKS 0548−322 (0.22–0.56), H1426+428 (0.12–0.49), IES 1959+650 (0.23–0.75) (M04; M08; Tramacere et al. 2007a; T09).

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\(^{12}\) The average values for these bands.
\[
\begin{align*}
\text{M04} & \text{ showed that a curved spectral distribution develops when the acceleration probability is a decreasing function of the electron energy (so-called energy-dependent acceleration probability process (EDAP)). In this scenario, a linear relation between the spectral parameters } a \text{ and } b \text{ was predicted as }
\begin{align*}
s &= -r \left( \frac{2}{q} \log \left( \frac{g}{\gamma_0} \right) \right) - \frac{q - 2}{2},
\end{align*}
\end{align*}
\]
where \( s = 2a + 1 \) and \( r = 4b \). This relation follows from the definition of the \( s \) and \( r \) parameters
\[
\begin{align*}
s &= -\frac{\log (g/\gamma_0)}{\log \varepsilon} - \frac{q - 2}{2},
\end{align*}
\]
and
\[
\begin{align*}
r &= \frac{q}{2} \log \varepsilon.
\end{align*}
\]
Here, \( g \) and \( q \) quantities are introduced as positive constants related to the probability \( P_i \) that a particle undergoes an acceleration step \( i \) given by
\[
P_i = g/\gamma_i^3,
\]
\( s \) is the particle’s energy gain at the acceleration step \( i \), and \( \gamma_i \) is the corresponding Lorentz factor. The absence of a significant correlation between \( a \) and \( b \) in PKS 2155–304 (see Section 4) leads to the suggestion that the EDAP process may be less relevant for the acceleration of the electrons responsible for X-ray flares in this source. Our result is in contrast to the BeppoSAX observations of Mrk 421 (M04) during 1997–1999 period where a strong correlation between these parameters was evident.

On the other hand, a curved spectral distribution can be established via the stochastic acceleration which arises from the magnetic turbulence close to the shock front (TO9, Massaro et al. (2011) showed that the electrons in the jets of TeV detected HBLs (so-called TBLs, including PKS 2155–304) should undergo a more efficient stochastic acceleration than in those of the TeV-undetected HBLs (UBLs). The same authors showed that the synchrotron SEDs are relatively broader (i.e. the curvature is smaller with \( b \geq 0.3 \)) when the stochastic acceleration is more efficient while they are narrower (\( b \leq 0.7 \)) in the opposite case. Our study of the curvature parameter from the XRT spectra of PKS 2155–304 shows its distribution maximum at \( b \approx 0.37 \), i.e. the source mainly exhibited broader synchrotron SEDs expected when the stochastic mechanism is more efficient. Furthermore, our detection of an anti-correlation between \( b \) and the 0.3–10 keV flux shows a trend of lower curvatures with higher fluxes (i.e. lower curvatures in flaring states) while the higher curvatures are observed mainly during the lower brightness states. This fact also favours the stochastic acceleration of the electrons producing X-ray emission during the flares. Unfortunately, we cannot study the \( E_p - b \) and \( E_p - S_p \) trends (since we have obtained upper limits to \( E_p \) from the X-ray analysis) and compare them with those predicted by the stochastic acceleration model in Tramacere, Massaro & Taylor (2011). This prevents us to draw further firm conclusions about the relevance of the stochastic acceleration for our target.

We also have examined if the trend of a decreasing curvature with higher 2–10 keV fluxes (obtained in this study) might serve as an indication of an increasing contribution of the photons of the IC origin to the X-rays that could cause a flattening in the hard part of X-ray spectrum which, on its turn, leads to a decrease of an downward curvature (\( b > 0 \)) and even the appearance of a negative curvature (see Zhang 2008). For this purpose, the broad-band SEDs were constructed for each XRT observation with a significant curvature, using the de-absorbed 0.3–2 keV and 2–10 keV model fluxes, derived via the spectral analysis, along with the contemporaneous multiwavelength data (Fig. 10). In the gamma-ray band, we used the spectral points extracted from the LAT observations and the VHE data from the literature (A09; Abramowski et al. 2010). For the lower part of the spectrum, we used our results from the UVOT observations and the SMARTS infrared-optical data (corrected for the Galactic absorption and converted into the cgs units). The radio data were taken from A09 and Abramowski et al. (2012). The lower and higher parts of each SED were fitted with the log-parabolic function (introduced by Landau et al. 1986)
\[
\log vF_v = A (\log v)^2 + B (\log v) + C,
\]
and with the cubic relation introduced by Comastri, Molendi & Ghisellini (1995)
\[
\log vF_v = a (\log v)^3 + b (\log v)^2 + c (\log v) + d.
\]
Both functions have been used by different authors to fit lower and higher energy parts of a BLL SED (e.g. Kubo et al. 1998; Nieppola, Tornikoski & Valtaoja 2006; Abdo et al. 2010). Note that the difference between the \( v_p \) values, calculated via the parabolic and cubic fit to the same synchrotron SED, generally corresponded to \( \Delta \log v_p \lesssim 0.2 \). These fits do not show a significant contribution of an IC emission to the X-ray part to the SED of PKS 2155–304 for any observation with curved spectra, in contrast to Zhang (2008).

The aforementioned fits to the broad-band synchrotron SEDs give \( v_p = 15.10–16.96 \) Hz for PKS 2155–304. Note that the SED peak was found in the optical energy range by (Zhang 2008) in the case of the XMM–Newton 2006 May and November pointings with the evidence of IC contribution to the X-ray spectra (log \( v_p \approx 14.38–14.73 \) Hz). It is clear that this object is a lower-energy peaked BLL compared to Mrk 501 (log \( v_p \approx 17.39–17.54 \) Hz\(^\text{13}\)), 1H 1426+428 (log \( v_p \approx 17.32–17.72 \) Hz), 1ES 1959+650 (log \( v_p \approx 17.30–17.66 \) Hz), PKS 0548–322 (log \( v_p \approx 17.74–18.03 \) Hz) (see Tramacere et al. 2007b; M08).

### 7 CONCLUSIONS
We have presented the results of a long-term XRT monitoring of the HBL PKS 2155–304. This source showed 0.3–10 keV fluxes characterized by \( F_{\text{max}}/F_{\text{min}} \approx 24 \) during 2005–2012. This range is significantly wider than those from shorter-term X-ray studies of our target. Despite the existence of significant gaps in the observations, several longer-time-scale variabilities (1–4 months, reported first time for this source) and short-term outbursts are revealed, with XRT-band flux changes by a factor of 2–7. The flaring activity of PKS 2155–304 showed an erratic character in this band (similar to other HBLs), with the different initial flux levels and periodic variations. The largest variability was recorded during the 2006 July–August campaign when the observed 0.3–10 keV flux dropped from 14.14 cts s\(^{-1}\) to about 2 cts s\(^{-1}\). Note that the source was more variable in the hard (2–10 keV) X-rays compared to the 0.3–2 keV energy band.

The source was variable in all spectral bands. Generally, we observe a trend of increasing variability amplitudes with higher frequencies. While the fluxes differ by a factor of \( \sim 7 \) in the UVOT

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\(^{13}\) These values are given in keVs in the original study. The same is for the HBLs below.
bands, the contemporaneous LAT and HESS observations yield $F_{\text{max}}/F_{\text{min}}$ ratio of 27 and 250 in the HE and VHE parts of the spectrum, respectively. Similar results have been reported for PKS 2155–304 in a few cases when the corresponding frequency ranges were very restricted ($\log (\Delta \nu) < 3$ Hz). We have expanded this study from the radio/IR bands to HE-VHE $\gamma$-rays for the different flaring epochs (11–16 orders of the frequency). The slopes of $F_{\nu}(E) \propto E^\alpha$ relation varied from flare to flare with $\alpha = 0.02$–0.12 and sometimes this trend was violated in the narrower frequency ranges (e.g. between the UVOT bands), mainly due to the sparsely sampled observations.

We have performed the first systematic search for X-ray IDVs in PKS 2155–304, and found 15 events at the 99.9 per cent confidence level with fractional variability amplitudes $F_{\text{var}} = 7.5$–30.0 per cent. The highest amplitude was recorded from the 2011 July 15 event when a fast ‘flash’ with $t_{\text{on}} = 0.4$ ks was superimposed on the longer-time-scale variability. Note that this is the shortest X-ray time-scale for this source to date and similar very fast events have been reported only from the VHE observations. Using the SF and ACF techniques, the time-scales of another seven events are derived which range from 9 ks to 40 ks. No correlation between the occurrence of intra-day variations and source brightness state is seen – they are found both in the maximum and in the intermediate/low states. The DC of these events is almost 50 per cent, that is much higher compared to that shown by HBLs in the optical bands (DC < 10 per cent; see e.g. Gaur et al. 2012; Kapanadze 2013). We plan to perform similar intensive studies also for other HBLs from the long-term XRT observations that will be useful to detect very fast X-ray fluctuations and draw statistical conclusions about the behaviour of these extreme sources on the subhour–several hr time-scales.

The spectra of PKS 2155–304 from the XRT observations are found to be mainly curved with the broad ranges of the parameters characterizing the logparabolic distribution of the emitted energy with frequencies. Our study has expanded significantly these ranges compared to those from the previous studies, performed for the restricted time intervals. The photon index at 1 keV varied both on weekly–monthly and intra-day time-scales ($2.05 \leq \alpha \leq 2.75$), and the source mainly showed a ‘harder-when-brighter’ spectral evolution. Sometimes, we observe consecutive changes to the opposite trends (from a CW loop into the CCW type and vice versa) which are mainly related to the short-term outbursts, accompanying the longer-term variability. The curvature parameter ranged between 0.13 and 0.80, and it showed anticorrelations with SED peak position, HR, and 0.3–10 keV flux. The lack of a correlation between photon index and curvature, predicted by the EDAP scenario, leads to the suggestion that EDAP is less relevant for the acceleration of the electrons responsible for X-ray flares in this source. We concluded that the stochastic acceleration of the electrons from the magnetic turbulence close to the shock front may be more important for this source since it showed mainly lower curvatures (i.e. broader synchrotron SEDs) during the X-ray flares expected when the stochastic mechanism is more efficient.

Since the source was significantly variable in the optical-UV part of the spectrum, the peak of the synchrotron SED, derived from the parabolic/cubic fit to the broad-band synchrotron SEDs, also shifted between the far-UV and the soft X-rays ($1.26 \times 10^{15}$ Hz to $\approx 10^{17}$). The upper limits, derived via the logparabolic fit to the 0.3–10 keV spectrum, were $5.24 \times 10^{15}$–$2.33 \times 10^{17}$ Hz. A shift of the SED peak towards the UV frequencies sometimes posed a difficulty in modelling the XRT spectrum with the logparabolic law whereas a simple power law gave a better fit in these cases.

We have found that the soft (0.3–2 keV) and hard (2–10 keV) fluxes were generally strongly correlated during 2005–2012 with the maximum soft lag of $\tau_{\text{soft}} \approx 7$ ks in the epoch of a relatively lower brightness while $\tau_{\text{soft}}$ was less than 1 ks in the higher states. This result is in agreement with some previous studies where a close cross-correlation was seen in the flaring states and it weakened for the lower fluxes, accompanied by an increase in the inter-band lags. Due to the sparsely sampled Swift observations, it was not possible to derive the values of inter-band lags on daily time-scales. In contrast to A09, we have not found a cubic relation between the X-ray and VHE $\gamma$-ray fluxes after the prominent 2006 July event. The X-ray flares were mostly accompanied by increasing activities in other spectral bands that is in favour of the one-zone SSC scenario. A clear exception was the 0.3–10 keV flare, observed during the 2010 August–October period without the lower and higher energy counterparts. It may be produced by the separate population of ultra-relativistic electrons which did not contribute significantly to the IR-UV and $\gamma$-ray parts of the spectrum. A lack of correlation between radio-IR variabilities with those in the higher-energy domain may be related to the generation of radio-IR emission in the blazar regions which are different from that responsible for the optical–$\gamma$-ray energy budget.

Our study of a long-term behaviour of PKS 2155–304 shows that the source was highly variable in the X-ray as well as in the optical, UV, and $\gamma$-ray bands, accompanied by a significant spectral variability that showed a complex and unpredictable character. Densely sampled Swift observations are necessary for a deeper study of unstable processes, responsible for these variations, and establish the ranges of inter-band lags. Similar investigations of other BLLs, being the targets of XRT, may be very useful to make a progress in our understanding of the blazar phenomenon.
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