High-energy properties of the high-redshift flat spectrum radio quasar PKS 2149–306

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ABSTRACT
We investigate the γ-ray and X-ray properties of the flat spectrum radio quasar PKS 2149–306 at redshift z = 2.345. A strong γ-ray flare from this source was detected by the Large Area Telescope on board the Fermi Gamma-ray Space Telescope satellite in 2013 January, reaching on January 20 a daily peak flux of \((301 \pm 36) \times 10^{-8} \text{ph cm}^{-2} \text{s}^{-1}\) in the 0.1–100 GeV energy range. This flux corresponds to an apparent isotropic luminosity of \((1.5 \pm 0.2) \times 10^{40} \text{erg s}^{-1}\), comparable to the highest values observed by a blazar so far. During the flare the increase of flux was accompanied by a significant change of the spectral properties. Moreover significant flux variations on a 6-h time-scale were observed, compatible with the light crossing time of the event horizon of the central black hole. The broad-band X-ray spectra of PKS 2149–306 observed by Swift-XRT and NuSTAR are well described by a broken power-law model, with a very hard spectrum (Γ1 ≈ 1) below the break energy, at \(E_{\text{break}} = 2.5–3.0 \text{ keV}\), and Γ2 ≈ 1.4–1.5 above the break energy. The steepening of the spectrum below \(\sim 3 \text{ keV}\) may indicate that the soft X-ray emission is produced by the low-energy relativistic electrons. This is in agreement with the small variability amplitude and the lack of spectral changes in that part of the X-ray spectrum observed between the two NuSTAR and Swift joint observations. As for the other high-redshift FSRQ detected by both Fermi-LAT and Swift-BAT, the photon index of PKS 2149–306 in hard X-ray is 1.6 or lower and the average γ-ray luminosity higher than \(2 \times 10^{48} \text{ erg s}^{-1}\).

Key words: galaxies: active – quasars: individual: PKS 2149–306 – quasars: general – gamma-rays: galaxies – gamma-rays: general – X-rays: galaxies.

1 INTRODUCTION

Blazars are radio-loud active galactic nuclei (AGN), with powerful relativistic jets observed at a small viewing angle. For this reason their emission is strongly enhanced due to Doppler boosting and they are expected to be detected up to high redshift. The most distant blazar identified so far is Q0906+6930 (Romani et al. 2004), located at redshift \(z = 5.47\). A possible excess of γ-ray photons from a position compatible with this flat spectrum radio quasar (FSRQ) was observed by EGRET (Romani 2006), but has not been confirmed by Fermi Large Area Telescope (LAT) observations so far. Recently, two FSRQ at redshift \(z > 5\), B2 1023+25 and SDSS J114657.79+403708.6, were detected in hard X-rays by NuSTAR and identified as blazars (Sbarra et al. 2013; Ghisellini et al. 2014a). Both objects have never been detected in γ rays. The most distant FSRQ reported in the Third Fermi-LAT catalogue (3FGL; Acero et al. 2015) is PKS 0537–286 at redshift \(z = 3.104\), indicating the difficulty in detecting quasars at \(z > 3\) in the γ-ray regime.

PKS 2149–306 (RA = 21h51m55.5239, Dec. = −30°27′53.697′′, J2000; Johnston et al. 1995) is an FSRQ at redshift \(z = 2.345\) (Wilkes 1986). The source is bright in X-rays, showing substantial variability both in intensity and spectral slope, as indicated by ROSAT (Siebert et al. 1996), ASCA (Cappi et al. 1997), XMM–Newton (Ferrero & Brinkmann 2003), and Swift observations (Sambruna et al. 2007; Bianchini et al. 2009). A tentative detection of an emission line at \(\sim 17 \text{ keV}\) in the source frame by ASCA was interpreted as highly blueshifted Fe Kα (Yaqoob et al. 1999). This finding was not confirmed by Fang et al. (2001) and Page et al. (2004) using Chandra data. As for other FSRQ, a low-energy photon deficit in X-rays was suggested for PKS 2149–306, possibly due to an absorbing cloud in the source rest frame (e.g. Sambruna et al. 2007) or to a low-energy tail of the electron population (e.g. Tavecchio et al. 2007). PKS 2149–306 was detected in hard X-rays with a hard spectrum by BeppoSAX (Elvis et al. 2000), Swift-BAT (Baumgartner et al. 2013), INTEGRAL–IBIS (Beckmann et al. 2009), and lately NuSTAR (Tagliaferri et al. 2015).

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Among the high-redshift (z > 2) blazars, 64 were reported in the 3FGL (Acero et al. 2015). Only two of these objects are at redshift z > 3. In contrast, 10 blazars at redshift z > 3 were detected in hard X-rays by Swift-BAT (Baumgartner et al. 2013), INTEGRAL-IBIS (Bassani et al. 2012), and NuSTAR (Sharrato et al. 2013; Ghisellini et al. 2014a). In particular, seven blazars at redshift z > 3 are detected by Swift-BAT. Therefore, observations in the hard X-ray band seem to be more effective than the γ-ray band for finding blazars at redshift z > 3. This might be due to the fact that high-redshift blazars generally have the inverse Compton (IC) peak at hundreds of keV and thus are not ideal for a detection at GeV energies (e.g. Ghisellini et al. 2011; Ghisellini 2013). For this reason, the detection of a γ-ray flare from a high-redshift blazar may be even more interesting with respect to the flaring activity from other blazars.

On 2013 January 4, a strong γ-ray flare from PKS 2149−306 was detected by Fermi-LAT (preliminary results were reported in D’Ammando & Orienti 2012). The aim of this paper is to discuss the γ-ray and X-ray properties of this source and to make a comparison with the other high-redshift blazars detected by Fermi-LAT and Swift-BAT using the 3FGL catalogue (Acero et al. 2015) and the 70-month Swift-BAT catalogue (Baumgartner et al. 2013). This paper is organized as follows. In Section 2, we report the LAT data analysis and results, while in Sections 3, 4, and 5 we present the results of the Swift, XMM–Newton, and NuSTAR observations, respectively. We discuss the properties of the source in Section 6, while in Section 7 we summarize our results. Throughout the paper, a Λ cold dark matter cosmology with H0 = 71 km s−1 Mpc−1, ΩM = 0.73, and ΩΛ = 0.27 is adopted (Komatsu et al. 2011). The corresponding luminosity distance at z = 2.345 (i.e. the source redshift) is dl = 19240 Mpc. Throughout the paper the quoted uncertainties are given at 1σ level, unless otherwise stated. For power-law (PL) spectra dN/dE ∝ E−Γ, and Γγ the spectral indices in the X-ray and γ-ray bands, respectively.

2 Fermi-LAT Data: Selection and Analysis

The Fermi-LAT is a pair-conversion telescope operating from 20 MeV to more than 300 GeV. It has a large peak effective area (∼8000 cm² for 1 GeV photons), and a field of view of about 2.4 sr with an angular resolution (68 per cent containment angle) of 0.6 for a single photon at E = 1 GeV on-axis. Details about the Fermi-LAT are given in Atwood et al. (2009).

The LAT data reported in this paper were collected from 2008 August 4 (MJD 54682) to 2014 August 4 (MJD 56873). During this period, the LAT instrument operated almost entirely in survey mode. The analysis was performed with the SCiEnevTOOl software package version v9r33p0. Only events belonging to the ‘Source’ class were used. In addition, a cut on the zenith angle (<100°) was applied to reduce contamination from the Earth limb γ rays, which are produced by cosmic rays interacting with the upper atmosphere. The spectral analysis was performed with the instrument response functions P7REP SOURCE_V15 using an unbinned maximum-likelihood method implemented in the Science tool gtlike (Mattox et al. 1996). The source model used in gtlike includes all the point sources from the 3FGL catalogue that fall within 15° of PKS 2149−306. The spectra of these sources were parametrized by a PL, a log parabola (LP), or a super exponential cut-off, as in the 3FGL catalogue. A first maximum-likelihood analysis was performed to remove from the model the sources having TS < 10 and/or the predicted number of counts based on the fitted model Npred < 1. A second maximum-likelihood analysis was performed on the updated source model. In the fitting procedure, the normalization factors and the spectral shape parameters of the sources lying within 10° of PKS 2149−306 were left as free parameters. For the sources located between 10° and 15° from our target, we kept the normalization and the spectral shape parameters fixed to the values from the 3FGL catalogue.

Integrating over the period 2008 August 4–2014 August 4 (MJD 54682–56873) using a PL model, dN/dE ∝ (E/E0)−Γ, the fit results in TS = 2096 in the 0.1–100 GeV energy range, and a photon index Γγ = 2.79 ± 0.03. The average flux is (10.6 ± 0.4) × 10−8 ph cm−2 s−1. In order to test for curvature in the γ-ray spectrum of PKS 2149−306 an alternative spectral model to a PL, an LP, dN/dE ∝ (E/E0)−Γ−αβ log(E/E0), was used for the fit. We obtain a spectral slope α = 2.36 ± 0.05 at the reference energy E0 = 221 MeV, a curvature parameter around the peak β = 0.29 ± 0.03, with TS = 2183 and an average flux of (9.7 ± 0.4) × 10−8 ph cm−2 s−1 (Table 1). We used a likelihood ratio test (LRT) to check the PL model (null hypothesis) against the LP model (alternative hypothesis). Following Nolan et al. (2012), these values may be compared by defining the curvature test statistic TScurve = TSLP−TSP, which in this case results in TScurve = 87 (~2σ). Thus, we have evidence of significant curvature in the average γ-ray spectrum.

Fig. 1 shows the γ-ray light curve for the first six years of Fermi-LAT observations of PKS 2149−306 using an LP model and 1-month time bins. For each time bin, the spectral shape parameters of PKS 2149−306 and all sources within 10° of it were frozen to the values resulting from the likelihood analysis over the entire period. If TS < 10, 2σ upper limits were calculated. The statistical

Table 1. Unbinned likelihood spectral fit results.

<table>
<thead>
<tr>
<th>Date (UT)</th>
<th>Date (MJD)</th>
<th>Γ</th>
<th>TSPL</th>
<th>α</th>
<th>β</th>
<th>TSLP</th>
<th>TSCurv</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008 Aug 04</td>
<td>54682–56873</td>
<td>2.79 ± 0.03</td>
<td>2096</td>
<td>2.36 ± 0.05</td>
<td>0.29 ± 0.03</td>
<td>2183</td>
<td>87</td>
</tr>
<tr>
<td>2011 Feb 03</td>
<td>55595–55625</td>
<td>2.85 ± 0.08</td>
<td>521</td>
<td>2.53 ± 0.13</td>
<td>0.28 ± 0.09</td>
<td>538</td>
<td>18</td>
</tr>
<tr>
<td>2013 Jan 04</td>
<td>56296–56325</td>
<td>2.45 ± 0.05</td>
<td>1239</td>
<td>1.99 ± 0.11</td>
<td>0.28 ± 0.06</td>
<td>1273</td>
<td>34</td>
</tr>
</tbody>
</table>

1 http://fermi.gsfc.nasa.gov/ssc/data/analysis/software/
2 http://fermi.gsfc.nasa.gov/ssc/data/access/lat/BackgroundModels.html
High-energy properties of FSRQ PKS 2149–306

Figure 1. Integrated flux light curve of PKS 2149–306 obtained by Fermi-LAT in the 0.1–100 GeV energy range during 2008 August 4–2014 August 4 (MJD 54682–56873) using an LP model with 30-day time bins. Arrows refer to 2σ upper limits on the source flux. Upper limits are computed when TS < 10. The dashed line represents the mean flux.

This difference may be related to the low statistics in the first two years that may prevent the detection of spectral curvature, as observed for other FSRQ (e.g. PKS 1510–089 and S5 0836+710; Abdo et al. 2010b; Akyuz et al. 2013). Flaring activity from this source was first observed in 2011 February, and subsequently an even stronger flare was detected in 2013 January (Fig. 1).

2.1 Flaring periods

Leaving the spectral shape parameters free to vary during the first high-activity period (2011 February 3–March 5; MJD 55595–55625), using an LP model, the fit results in a spectral slope α = 2.53 ± 0.13 at the reference energy E0 = 221 MeV, a curvature parameter around the peak β = 0.28 ± 0.09, with TS = 538 and an average flux of (51.3 ± 4.1) × 10−8 ph cm−2 s−1. Using a PL model, the fit results in TS = 521 and a photon index of γ = 2.85 ± 0.08 (Table 1). Using an LRT, we obtain TS_{curve} = 18 (~4.2σ), i.e. a significant curvature of the γ-ray spectrum in 2011 February.

During the second high-activity period (2013 January 4–February 2; MJD 56296–56325), using an LP model the fit results in a spectral slope α = 1.99 ± 0.11 at the reference energy E0 = 221 MeV, a curvature parameter around the peak β = 0.28 ± 0.06, with TS = 1273 and an average flux of (77.4 ± 5.1) × 10−8 ph cm−2 s−1. Using a PL model the fit results in TS = 1239 and a photon index of γ = 2.45 ± 0.05 (Table 1). Using an LRT, we obtain TS_{curve} = 34 (~5.8σ), indicating a significant curvature of the γ-ray spectrum in that period.

In the following analysis of the light curves on sub-daily timescales, we fixed the flux of the diffuse emission components at the value obtained by fitting the data over the respective daily time-bins. In Fig. 2, we show a light curve focused on the period 2011 February 3–March 5 (left-hand plot) and 2013 January 4–February 2 (right-hand plot), with 1-day (upper panel), 12-h (middle panel), and 6-h (lower panel) time bins. For each time bin, the spectral shape parameters of PKS 2149–306 and all sources within 10° of...
the X-ray Telescope observations were performed with all three instruments on board: SWIFT 0.1–100 GeV energy range, a factor of about 14 higher than the average flux over six years of Fermi observations. The corresponding apparent isotropic γ-ray luminosity peak in the 0.1–100 GeV energy range is \((5.3 \pm 0.9) \times 10^{39} \text{ erg s}^{-1}\). On 12-h and 6-h time-scale the observed peak flux is \((157 \pm 37) \times 10^{-8} \text{ ph cm}^{-2} \text{ s}^{-1}\) and \((180 \pm 47) \times 10^{-8} \text{ ph cm}^{-2} \text{ s}^{-1}\), corresponding to an apparent isotropic γ-ray luminosity of \((5.9 \pm 1.3) \times 10^{39}\) and \((6.8 \pm 1.7) \times 10^{39}\) erg s\(^{-1}\), respectively.

In 2013, the daily peak of the emission was observed on January 20 (MJD 56312) with a flux of \((301 \pm 36) \times 10^{-8} \text{ ph cm}^{-2} \text{ s}^{-1}\) in the 0.1–100 GeV energy range, i.e. a factor of about 30 higher than the average flux over six years of Fermi observations. The corresponding apparent isotropic γ-ray luminosity peak in the 0.1–100 GeV energy range is \((1.5 \pm 0.2) \times 10^{39} \text{ erg s}^{-1}\). On 12-h and 6-h time-scales the observed peak flux is \((335 \pm 48) \times 10^{-8} \text{ and} (385 \pm 70) \times 10^{-8} \text{ ph cm}^{-2} \text{ s}^{-1}\), corresponding to an apparent isotropic γ-ray luminosity of \((1.6 \pm 0.2) \times 10^{39}\) and \((1.9 \pm 0.3) \times 10^{39}\) erg s\(^{-1}\), respectively. By means of the gtspcreprob tool, we estimated that during this flare the highest energy photon emitted by PKS 2149–306 (with probability >80 per cent to be associated with the target) was observed on 2013 January 12 with an energy of 4.8 GeV.

### 3 Swift Data: Analysis and Results

The Swift satellite (Gehrels et al. 2004) performed 16 observations of PKS 2149–306 between 2005 December and 2014 April. The observations were performed with all three instruments on board: the X-ray Telescope (XRT; Burrows et al. 2005, 0.2–10.0 keV), the Ultraviolet/Optical Telescope (UVOT; Roming et al. 2005, 170–600 nm) and the Burst Alert Telescope (BAT; Barthelmy et al. 2005, 15–150 keV).

#### 3.1 Swift-BAT

The hard X-ray flux of this source is below the sensitivity of the BAT instrument for the short exposures of the single observations, therefore those data from this instrument were not used. On the other hand, the source is included in the Swift-BAT 70-month hard X-ray catalogue (Baumgartner et al. 2013). The 14–195 keV spectrum is well described by a PL with photon index of \(\Gamma_X = 1.50 \pm 0.10\). The model that best fits this observation is a broken PL (see Section 3.2).

<table>
<thead>
<tr>
<th>Date (UT)</th>
<th>Date (MJD)</th>
<th>Net exposure time (s)</th>
<th>Photon index ((\Gamma_X))</th>
<th>Flux 0.3–10 keV ((\times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}))</th>
<th>(\chi^2/\text{d.o.f.})</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005 Dec 10</td>
<td>53714</td>
<td>3314</td>
<td>1.47 ± 0.08</td>
<td>1.52 ± 0.12</td>
<td>44/45</td>
</tr>
<tr>
<td>2005 Dec 13</td>
<td>53717</td>
<td>2255</td>
<td>1.39 ± 0.10</td>
<td>1.69 ± 0.10</td>
<td>32/25</td>
</tr>
<tr>
<td>2009 Apr 29</td>
<td>54950</td>
<td>1773</td>
<td>1.34 ± 0.14</td>
<td>1.21 ± 0.09</td>
<td>16/16</td>
</tr>
<tr>
<td>2009 May 05</td>
<td>54956</td>
<td>2889</td>
<td>1.36 ± 0.10</td>
<td>1.22 ± 0.07</td>
<td>28/28</td>
</tr>
<tr>
<td>2009 May 14</td>
<td>54965</td>
<td>2924</td>
<td>1.32 ± 0.08</td>
<td>1.75 ± 0.07</td>
<td>40/41</td>
</tr>
<tr>
<td>2009 May 23</td>
<td>54974</td>
<td>2989</td>
<td>1.40 ± 0.11</td>
<td>1.58 ± 0.09</td>
<td>31/28</td>
</tr>
<tr>
<td>2009 May 29</td>
<td>54980</td>
<td>2566</td>
<td>1.19 ± 0.08</td>
<td>1.91 ± 0.10</td>
<td>39/36</td>
</tr>
<tr>
<td>2010 May 11</td>
<td>55327</td>
<td>4760</td>
<td>1.30 ± 0.08</td>
<td>1.17 ± 0.05</td>
<td>38/44</td>
</tr>
<tr>
<td>2011 May 07</td>
<td>55688</td>
<td>2947</td>
<td>1.01 ± 0.09</td>
<td>1.96 ± 0.12</td>
<td>35/38</td>
</tr>
<tr>
<td>2011 Nov 10</td>
<td>55875</td>
<td>3261</td>
<td>1.33 ± 0.07</td>
<td>1.87 ± 0.09</td>
<td>39/48</td>
</tr>
<tr>
<td>2013 Dec 16/17</td>
<td>56644/43</td>
<td>7956</td>
<td>1.09 ± 0.04</td>
<td>2.80 ± 0.08</td>
<td>143/139</td>
</tr>
<tr>
<td>2014 Mar 28</td>
<td>56744</td>
<td>2537</td>
<td>1.13 ± 0.08</td>
<td>2.58 ± 0.11</td>
<td>47/44</td>
</tr>
<tr>
<td>2014 Apr 18</td>
<td>56765</td>
<td>6331</td>
<td>1.08 ± 0.05</td>
<td>2.60 ± 0.07</td>
<td>126/106</td>
</tr>
</tbody>
</table>

**Note.** The model that best fits this observation is a broken PL (see Section 3.2).

3.2 Swift-XRT

The XRT data were processed with standard procedures, filtering, and screening criteria by using the xrtpipeline v0.13.0 included in the HEASOFT package (v6.15). The data were collected in photon counting mode for all the observations. The source count rate was low (<0.5 counts s\(^{-1}\)); thus pile-up correction was not required. The data collected in observations separated by less than 24 hours (i.e. 2010 May 11, obsid: 31404008 and 31404009; 2011 May 7, obsid: 31404010 and 31404011; 2013 December 16–17, obsid: 31404013 and 31404014) were summed in order to have enough statistics to obtain a good spectral fit. Source events were extracted from a circular region with a radius of 20 pixels (1 pixel ~2.36 arcsec; Burrows et al. 2005), while background events were extracted from a circular region with radius of 50 pixels far away from bright sources. Ancillary response files were generated with xrtmkarf, and account for different extraction regions, vignetting and point spread function corrections. We used the spectral redistribution matrices in the Calibration data base (CALDB) maintained by HEASARC. The spectra were rebinned with a minimum of 20 counts per energy bin to allow for \(\chi^2\) spectrum fitting. Bad channels, including zero-count bins, were ignored in the fit. We have fitted the spectrum using xspec with an absorbed PL using the photoelectric absorption model tbabs (Wilms, Allen & McCray 2000), with a neutral hydrogen column density fixed to its Galactic value (1.63 \(\times 10^{20}\) cm\(^{-2}\); Kalberla et al. 2005). The results are reported in Table 2. All errors are given at the 90 per cent confidence level. Symmetric errors are reported, obtained by averaging the positive and negative errors calculated with xspec.

Note: http://heasarc.nasa.gov/heasoft/

\(^{3}\) http://heasarc.gsfc.nasa.gov/HEASOFT/

\(^{4}\) http://heasarc.gsfc.nasa.gov/

Table 3. Observed magnitudes obtained by Swift–UVOT for PKS 2149–306. Upper limits are calculated when the analysis provided a significance of detection $<3\sigma$.

<table>
<thead>
<tr>
<th>Date (UT)</th>
<th>Date (MJD)</th>
<th>v</th>
<th>b</th>
<th>u</th>
<th>u1</th>
<th>m2</th>
<th>u2</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005 Dec 10</td>
<td>53714</td>
<td>17.46 ± 0.14</td>
<td>17.76 ± 0.12</td>
<td>17.15 ± 0.11</td>
<td>17.92 ± 0.14</td>
<td>20.22 ± 0.41</td>
<td>19.79 ± 0.25</td>
</tr>
<tr>
<td>2005 Dec 13</td>
<td>53717</td>
<td>17.56 ± 0.21</td>
<td>17.55 ± 0.15</td>
<td>17.02 ± 0.12</td>
<td>18.12 ± 0.19</td>
<td>19.63 ± 0.20</td>
<td>20.16 ± 0.44</td>
</tr>
<tr>
<td>2009 Apr 23</td>
<td>54944</td>
<td>17.94 ± 0.23</td>
<td>17.88 ± 0.13</td>
<td>17.30 ± 0.13</td>
<td>18.59 ± 0.22</td>
<td>&gt;19.82</td>
<td>&gt;20.37</td>
</tr>
<tr>
<td>2009 Apr 29</td>
<td>54950</td>
<td>17.85 ± 0.23</td>
<td>18.22 ± 0.16</td>
<td>17.65 ± 0.15</td>
<td>18.73 ± 0.27</td>
<td>&gt;19.45</td>
<td>&gt;20.21</td>
</tr>
<tr>
<td>2009 May 05</td>
<td>54956</td>
<td>17.32 ± 0.16</td>
<td>17.82 ± 0.13</td>
<td>17.35 ± 0.14</td>
<td>18.52 ± 0.24</td>
<td>&gt;19.69</td>
<td>&gt;20.25</td>
</tr>
<tr>
<td>2009 May 14</td>
<td>54965</td>
<td>17.65 ± 0.17</td>
<td>17.99 ± 0.12</td>
<td>17.17 ± 0.12</td>
<td>18.32 ± 0.19</td>
<td>&gt;19.84</td>
<td>&gt;20.44</td>
</tr>
<tr>
<td>2009 May 23</td>
<td>54974</td>
<td>17.79 ± 0.16</td>
<td>18.08 ± 0.11</td>
<td>17.34 ± 0.11</td>
<td>18.24 ± 0.16</td>
<td>&gt;20.04</td>
<td>&gt;20.20</td>
</tr>
<tr>
<td>2009 May 29</td>
<td>54980</td>
<td>17.82 ± 0.23</td>
<td>17.71 ± 0.11</td>
<td>17.25 ± 0.12</td>
<td>18.42 ± 0.19</td>
<td>&gt;19.54</td>
<td>20.36 ± 0.39</td>
</tr>
<tr>
<td>2010 May 11</td>
<td>55327</td>
<td>17.84 ± 0.09</td>
<td>17.25 ± 0.08</td>
<td>17.64 ± 0.08</td>
<td>18.38 ± 0.10</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>2010 Nov 07</td>
<td>55688</td>
<td>17.56 ± 0.07</td>
<td>17.95 ± 0.10</td>
<td>18.12 ± 0.08</td>
<td>–</td>
<td>–</td>
<td>20.12 ± 0.22</td>
</tr>
<tr>
<td>2013 Dec 16</td>
<td>56642</td>
<td>17.87 ± 0.16</td>
<td>17.92 ± 0.10</td>
<td>17.22 ± 0.10</td>
<td>18.31 ± 0.14</td>
<td>19.92 ± 0.30</td>
<td>20.24 ± 0.28</td>
</tr>
<tr>
<td>2013 Dec 17</td>
<td>56643</td>
<td>17.57 ± 0.18</td>
<td>18.14 ± 0.15</td>
<td>17.23 ± 0.12</td>
<td>18.22 ± 0.18</td>
<td>&gt;19.54</td>
<td>&gt;20.20</td>
</tr>
<tr>
<td>2014 Mar 28</td>
<td>56744</td>
<td>17.80 ± 0.20</td>
<td>17.87 ± 0.11</td>
<td>17.24 ± 0.11</td>
<td>18.31 ± 0.17</td>
<td>&gt;19.75</td>
<td>20.35 ± 0.36</td>
</tr>
<tr>
<td>2014 Apr 18</td>
<td>56765</td>
<td>17.79 ± 0.17</td>
<td>17.92 ± 0.10</td>
<td>17.24 ± 0.10</td>
<td>18.61 ± 0.17</td>
<td>&gt;20.06</td>
<td>20.34 ± 0.32</td>
</tr>
</tbody>
</table>

Table 4. Summary of fits to the 0.3–10 keV XMM–Newton spectrum of PKS 2149–306. Fits also included absorption fixed at the Galactic value. Flux and $E_{\text{break}}$ are given in units of erg cm$^{-2}$ s$^{-1}$ and keV, respectively.

<table>
<thead>
<tr>
<th>Model</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>PL</td>
<td>$\Gamma$</td>
<td>1.45 ± 0.01</td>
</tr>
<tr>
<td></td>
<td>Flux (0.3–10 keV)</td>
<td>(7.9 ± 0.1) $\times 10^{-12}$</td>
</tr>
<tr>
<td></td>
<td>$\chi^2$/d.o.f.</td>
<td>375/428</td>
</tr>
<tr>
<td>Broken PL</td>
<td>$\Gamma_1$</td>
<td>1.47 ± 0.02</td>
</tr>
<tr>
<td></td>
<td>$E_{\text{break}}$</td>
<td>2.4$^{+1.3}_{-1.1}$</td>
</tr>
<tr>
<td></td>
<td>$\Gamma_2$</td>
<td>1.42$^{+0.03}_{-0.07}$</td>
</tr>
<tr>
<td></td>
<td>Flux (0.3–10 keV)</td>
<td>(7.9 ± 0.2) $\times 10^{-12}$</td>
</tr>
<tr>
<td></td>
<td>$\chi^2$/d.o.f.</td>
<td>369/426</td>
</tr>
</tbody>
</table>

For the observations performed on 2013 December 16–17 and 2014 April 18 there is enough statistic for testing a more detailed spectral model with respect to a simple PL. For the 2013 December observations, using a broken PL the fit results in $\Gamma_1 = 0.95^{+0.08}_{-0.13}$ below the break energy $E_{\text{break}} = 2.40^{+0.04}_{-0.02}$ keV and $\Gamma_2 = 1.32^{+0.16}_{-0.15}$ above $E_{\text{break}}$. The fit with a broken PL ($\chi^2$/d.o.f = 129/137) does not improve with respect to a simple PL ($\chi^2$/d.o.f = 143/139). For the 2014 April observation using a broken PL the fit results in $\Gamma_1 = 0.97 ± 0.09$ below the break energy $E_{\text{break}} = 2.76^{+0.33}_{-0.81}$ keV and $\Gamma_2 = 1.34^{+0.35}_{-0.36}$ above $E_{\text{break}}$ ($\chi^2$/d.o.f = 116/104). The F-test shows an improvement of the fit with respect to the simple PL ($\chi^2$/d.o.f = 126/106) with a probability of 97.9 per cent, indicating that the broken PL is the best-fitting model.

3.3 Swift–UVOT

UVOT data in the $v$, $b$, $u$, $w1$, $m2$, and $w2$ filters were analysed with the uvotsource task included in the HEASOFT package (v6.15) and the 20130118 CALDB-UVOTA release. Source counts were extracted from a circular region of 5 arcsec radius centred on the source, while background counts were derived from a circular region with 10 arcsec radius in a nearby, free region. The observed magnitudes are reported in Table 3. Upper limits at 90 per cent confidence level are calculated using the UVOT photometric system when the analysis provided a significance of detection $<3\sigma$.

4 XMM–NEWTON: DATA ANALYSIS AND RESULTS

XMM–Newton (Jansen et al. 2001) observed PKS 2149–306 on 2001 May 1 for a total duration of 25 ks (observation ID 0103060401, PI: Aschenbach). The EPIC pn was operated in the large-window mode and the EPIC MOS cameras (MOS1 and MOS2) were operated in the full-frame mode. The data were reduced using the XMM–Newton Science Analysis System (SAS v14.0.0), applying standard event selection and filtering. Inspection of the background light curves showed that no strong flares were present during the observation, with good exposure times of 20, 24 and 24 ks for the pn, MOS1 and MOS2, respectively. For each of the detectors the source spectrum was extracted from a circular region of radius 30 arcsec centred on the source, and the background spectrum from a nearby region of radius 30 arcsec on the same chip. All the spectra were binned to contain at least 20 counts per bin to allow for $\chi^2$ spectral fitting.

All spectral fits were performed over the 0.3–10 keV energy range using XSPEC v12.8.2. The energies of spectral features are quoted in the source rest frame, while plots are in the observer frame. All errors are given at the 90 per cent confidence level. The data from the three EPIC cameras were initially fitted separately, but since good agreement was found (<5 per cent) we proceeded to fit them together. Galactic absorption was included in all fits using the tbabs model. The results of the fits are presented in Table 4. As reported also in Ferrero & Brinkmann (2003) and Bianchin et al. (2009), a simple PL model is sufficient to describe the data, although some residuals are present (Fig. 3). The flux observed by XMM–Newton in the 0.3–10 keV energy range is a factor of 2–3 lower than those observed by Swift–XRT during 2005–2014.

A broken PL does not improve the fit and the associated uncertainties on photon index and flux are larger than those from a fit with a simple PL (Table 4). In order to check for the presence of intrinsic absorption, a neutral absorber at the redshift of the source was added to this model, but it did not improve the fit quality and thus is not required. Moreover, no Iron line was detected in the spectrum, in agreement with Page et al. (2004). The 90 per cent upper limit on the equivalent width (EW) of a narrow emission line at 6.4 keV is $\text{EW} < 17$ eV.

Downloaded from http://mnras.oxfordjournals.org/ at California Institute of Technology on February 4, 2016
Figure 3. EPIC spectra and residuals of PKS 2149–306 fitted with a PL model.

Table 5. Summary of the results for the fits of the 3.0–76 keV NuSTAR spectra collected on 2013 December 17 and 2014 April 18.

<table>
<thead>
<tr>
<th>Date</th>
<th>Photon index $\Gamma_X$</th>
<th>Flux 3.0–76 keV $\times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$</th>
<th>$\chi^2$/d.o.f.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2013 Dec 17</td>
<td>1.37 ± 0.01</td>
<td>11.5 ± 0.2</td>
<td>797/805</td>
</tr>
<tr>
<td>2014 Apr 18</td>
<td>1.46 ± 0.01</td>
<td>8.2 ± 0.1</td>
<td>735/747</td>
</tr>
</tbody>
</table>

5 NuSTAR: DATA ANALYSIS AND RESULTS

NuSTAR (Harrison et al. 2013) observed PKS 2149–306 with its two coaligned X-ray telescopes with corresponding focal planes, focal plane module A (FPMA) and B (FPMB), on 2013 December 17 and on 2014 April 18 for a net exposure time of 38.5 ks and 44.1 ks, respectively. The level 1 data products were processed with the NuSTAR Data Analysis Software (NUSTARDAS) package (v1.4.1). Cleaned event files (level 2 data products) were produced and calibrated using standard filtering criteria with the NUPPIPELINE task and version 20140414 of the calibration files available in the NuSTAR CALDB. Spectra of the sources were extracted from the cleaned event files using a circle of 20 pixel (49 arcsec) radius, while the background was extracted from two distinct nearby circular regions of 50 pixel radius. The ancillary response files were generated with the numcarf task, applying corrections for the point spread function losses, exposure maps and vignetting. The spectra were rebinned with a minimum of 20 counts per energy bin to allow for $\chi^2$ spectrum fitting. All errors are given at the 90 per cent confidence level.

By fitting the NuSTAR spectrum in the 3–76 keV energy range a good fit was obtained using a simple PL for both the observations ($\chi^2$/d.o.f. = 797/805 and 735/747), with photon index $\Gamma_X = 1.37 ± 0.01$ and $\Gamma_Y = 1.46 ± 0.01$ (Table 5), that is the same value obtained for $\Gamma_Y$ with a broken PL model over the 0.3–76 keV energy range (see Section 5.1).

5.1 Joint NuSTAR and Swift-XRT analysis

Simultaneously to NuSTAR observations, Swift-XRT observations were performed on 2013 December 16–17 and on 2014 April 18.

Table 6. Summary of the results for the fits of the 0.3–76 keV Swift-XRT and NuSTAR spectra collected on 2013 December 16–17 (Obs 1) and 2014 April 18 (Obs 2). All fits also included absorption fixed at the Galactic value.

<table>
<thead>
<tr>
<th>Model</th>
<th>Parameter</th>
<th>Value (Obs 1)</th>
<th>Value (Obs 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PL</td>
<td>$\Gamma$</td>
<td>1.35 ± 0.01</td>
<td>1.43 ± 0.01</td>
</tr>
<tr>
<td></td>
<td>$\chi^2$/d.o.f.</td>
<td>1013/943</td>
<td>983/851</td>
</tr>
<tr>
<td>Broken PL</td>
<td>$\Gamma_1$</td>
<td>0.97 ± 0.09</td>
<td>0.97 ± 0.09</td>
</tr>
<tr>
<td></td>
<td>$E_{\text{break}}$ (keV)</td>
<td>2.60 ± 0.46</td>
<td>2.60 ± 0.46</td>
</tr>
<tr>
<td></td>
<td>$\Gamma_2$</td>
<td>1.37 ± 0.01</td>
<td>1.46 ± 0.01</td>
</tr>
<tr>
<td></td>
<td>$\chi^2$/d.o.f.</td>
<td>924/941</td>
<td>834/849</td>
</tr>
<tr>
<td>PL + Extra absorber</td>
<td>$N_H$ (cm$^{-2}$)</td>
<td>$1.01 ± 0.28 \times 10^{22}$</td>
<td>$1.36 ± 0.39 \times 10^{22}$</td>
</tr>
<tr>
<td></td>
<td>$\chi^2$/d.o.f.</td>
<td>966/942</td>
<td>895/850</td>
</tr>
</tbody>
</table>

This allows us to study the X-ray spectrum of PKS 2149–306 over a wide energy range, i.e. 0.3–76 keV. The results of the simultaneous fits of the NuSTAR and Swift-XRT data are presented in Table 6. The photoelectric absorption model t$babs$, with a neutral hydrogen column density fixed to its Galactic value ($1.63 \times 10^{20}$ cm$^{-2}$) was included in all fits. To account for the cross-calibration between NuSTAR-FPMA, NuSTAR-FPMB, and Swift-XRT a constant factor was included in the model, frozen at 1 for the EPIC spectra and free to vary for the FPMB and XRT spectra. The X-ray spectrum of the source is not well fitted by a simple PL model in both the observations ($\chi^2$/d.o.f. = 1013/943 and 983/851, for the first and second observation, respectively), while a broken PL model yielded a good fit ($\chi^2$/d.o.f. = 924/941 and 834/849). The result of fitting a broken PL to the spectrum collected on 2013 December 16–17 is shown in Fig. 4. In this model, the PL breaks from a slope of $\Gamma_1 = 0.97 ± 0.09$ ($\Gamma_1 = 0.97 ± 0.09$ below $E_{\text{break}} = 2.60 ± 0.46$ keV) to $\Gamma_2 = 1.37 ± 0.01$ ($\Gamma_2 = 1.46 ± 0.01$) for the first (second) observation (Table 6). The difference of the cross-calibration for the FPMB spectra with respect to EPIC spectra is 1–3 per cent, while for the XRT spectra is less than 10 per cent. These differences become larger (10–30 per cent) when a simple PL model is used. By applying an F-test, the improvement of the fit with a broken PL is significant with respect to a simple PL, with a probability that the null hypothesis is true of 1.6 $\times 10^{-19}$ and 5 $\times 10^{-31}$ for the first and second observation, respectively. These results are in agreement with those reported in Tagliaferri et al. (2015). By adding an extra absorption component at the redshift of the source ($z\ t$babs$) to the single PL,
the model provides a good fit to the spectrum, with an equivalent hydrogen column density of \( \sim 10^{22} \) cm\(^{-2}\), but the quality of the fit is worse than the broken PL model in both spectra (\( \chi^2/\text{d.o.f.} = 966/942 \) and 895/850; Table 6). Sambruna et al. (2007) reported an equivalent hydrogen column density obtained by the fit of Swift XRT and BAT spectra of \( 0.25^{+0.34}_{-0.25} \times 10^{22} \) cm\(^{-2}\), that is lower than the values obtained by fitting the Swift-XRT and NuSTAR spectra, but their statistics was significantly lower than that presented here.

6 DISCUSSION

6.1 \( \gamma \)-ray properties

PKS 2149–306 was not associated with a \( \gamma \)-ray source, either in the LAT bright source list obtained after three months of Fermi operation (Abdo et al. 2009) or in the First Fermi LAT source catalogue (Abdo et al. 2010a), indicating that its \( \gamma \)-ray activity was low during the first year of Fermi operation. On the other hand, this FSRQ is associated with 2FGL J2151.5–3021 and 3FGL J2151.8–3025 in the Second and Third Fermi LAT source catalogues (Nolan et al. 2012; Acero et al. 2015). The source is not included in the First Fermi LAT Catalog of Sources above 10 GeV (Ackermann et al. 2013). During the period 2008 August 4–2014 August 4, the \( \gamma \)-ray spectrum of PKS 2149–306 shows significant curvature, well described by an LP model with a spectral slope \( \alpha = 2.36 \pm 0.05 \), a curvature parameter around the peak \( \beta = 0.29 \pm 0.03 \), and an average flux of \( (9.7 \pm 0.4) \times 10^{-8} \) ph cm\(^{-2}\) s\(^{-1}\).

The source showed a significant increase in its \( \gamma \)-ray flux in 2011 February, and subsequently a strong \( \gamma \)-ray flare occurred in 2013 January (D’Ammando & Orienti 2012). The flux in 2013 January is about a factor of 8 higher than the average flux estimated over 6 yr of Fermi observations, with a significant change of the spectral slope \((\alpha = 1.99 \pm 0.11)\) but a similar curvature parameter \((\beta = 0.28 \pm 0.06)\). This suggests a shift of the IC peak to higher energies during this flaring activity. In contrast, no significant spectral changes were observed during the flaring activity in 2011 February, when the flux was about a factor of 5 higher than the average flux. In both flaring episodes the \( \gamma \)-ray spectrum is well described by an LP model. Considering the extragalactic background light (EBL) model discussed in Finke, Razzano & Dermer (2010), at the redshift of PKS 2149–306 the optical depth should be \( \tau \sim 1 \) for 50 GeV photons. The maximum photon energy observed from the source during the 2013 flare is 4.8 GeV and is consistent with the current EBL models.

Thirteen FSRQ with \( z > 2 \) have been detected by Fermi-LAT during a \( \gamma \)-ray flare up to now. A significant increase of the flux together with a spectral evolution in \( \gamma \) rays was observed for the high-redshift FSRQ TXS 0536+145 (Orienti et al. 2014) and S5 0836+710 (Akyuz et al. 2013). In contrast, no significant spectral hardening was observed during the \( \gamma \)-ray flares for the high-redshift gravitationally lensed blazar PKS 1830–211 (Abdo et al. 2015).

During the 2013 flaring activity of PKS 2149–306, significant flux variation by a factor of 2 or more is clearly visible on 12-h and 6-h time-scales, with the peak of the flare resolved with 6-h binning. In particular, between the last 6-h bin of January 19 (MJD 56311.875) and the second 6-h bin of January 20 (MJD 56312.625), the flux increases from \( F_1 = (88 \pm 40) \times 10^{-8} \) ph cm\(^{-2}\) s\(^{-1}\) to \( F_2 = (385 \pm 64) \times 10^{-8} \) ph cm\(^{-2}\) s\(^{-1}\) within \( \Delta t = 12 \) h, giving a flux doubling time-scale of \( r_d = \Delta t / \ln 2 / (\ln(F_2/F_1)) \approx 5.6 \) h, and an exponential growth time-scale of \( r_g / \ln2 \approx 8 \) h.

The event horizon light crossing time of a supermassive black hole (SMBH) is \( t_{\text{eh}} \sim r_h/c = G M_0/c^3 \sim 1.4 \times 10^8 M_0 \) h, where \( r_h \) is the gravitational radius, \( M_0 = (M/10^9) M_\odot \) is the black hole (BH) mass, and \( c \) the speed of light (e.g. Begelman, Fabian & Rees 2008).

In the case of PKS 2149–306, with a BH mass of \( 3.5 \times 10^9 M_\odot \) (Tagliaferri et al. 2015), we obtain \( t_{\text{eh}} \sim 5 \) h, compatible with the minimum variability detected in the LAT light curve during 2013 January. This short time variability observed in \( \gamma \) rays constrains the size of the emitting region to \( R < c t_{\text{eh}}/\delta (1+z) = 2.7 \times 10^{15} \) cm (assuming \( \delta = 14 \); Tagliaferri et al. 2015). This small size of the emitting region should correspond to a small distance from the central BH, putting the emitting region inside the broad-line region (BLR). This extremely small size is rather difficult to accommodate in the ‘far dissipation’ scenario (e.g. Tavecchio et al. 2010), where the external Compton scattering off the infrared photons from the torus is the main component that produces the high-energy emission, at least during flaring activity. This is not in contrast to the SED modelling of PKS 2149–306 presented in Tagliaferri et al. (2015), where low \( \gamma \)-ray activity contemporaneous to the NuSTAR observations was considered. In fact, different activity states of the same source may have different \( \gamma \)-ray emitting region locations. In the case of the 2011 February flare the statistics are not good enough to determine the flare shape.

High-redshift blazars tend to be the most luminous AGN due to their preferential selection by the LAT caused by Malmquist bias (Ackermann et al. 2015). The daily peak flux observed on 2013 January 20 is \( (301 \pm 36) \times 10^{-8} \) ph cm\(^{-2}\) s\(^{-1}\), corresponding to an apparent isotropic \( \gamma \)-ray luminosity of \( (1.5 \pm 0.2) \times 10^{50} \) erg s\(^{-1}\). On a 6-h time-scale, the flux reached a peak of \( (385 \pm 70) \times 10^{-8} \) ph cm\(^{-2}\) s\(^{-1}\), corresponding to an apparent isotropic \( \gamma \)-ray luminosity of \( (1.9 \pm 0.3) \times 10^{50} \) erg s\(^{-1}\). As a comparison, the average \( \gamma \)-ray luminosity over 6 yr of Fermi operation is \( 4.4 \times 10^{49} \) erg s\(^{-1}\). The peak values are comparable to the highest luminosity observed from FSRQ so far (i.e. 3C 454.3 and PKS 1830–211; Ackermann et al. 2010; Abdo et al. 2015) and a factor of two higher than the peak luminosity observed from TXS 0536+135, that is the most distant \( \gamma \)-ray flaring blazar observed by Fermi-LAT up to now (Orienti et al. 2014). In Fig. 5, we compare this value with the \( \gamma \)-ray luminosity of all blazars with \( z > 2 \) included in the 3FGL. We consider the
high-redshift blazars detected also by Swift-BAT in hard X-rays. In particular, in the 70-month Swift-BAT catalogue (Baumgartner et al. 2013) there are 17 blazars with redshift \( z > 2 \). The filled and open triangles in Fig. 5 represent the blazars detected and not detected by Swift-BAT, respectively. The \( \gamma \)-ray luminosity, \( L_\gamma \), is computed following Ghisellini, Maraschi & Tavecchio (2009):

\[
L_\gamma = 4 \pi d^2 \frac{S_\gamma}{(1+z)^2 \Gamma_\gamma^2}
\]

where \( S_\gamma \) is the energy flux between 100 MeV and 100 GeV, and \( \Gamma_\gamma \) is the photon index.

All these high-redshift blazars are FSRQ, with the exception of SDSS J145059.99+520111.7, PMN J0124-0624, MG4 J000800+4712, and PKS 0437-454 classified as BL Lac objects. Considering the average luminosity, PKS 2149–306 is the third brightest object among the high-redshift blazars detected by LAT, after PKS 1830–211 and PKS 0537–286.

By considering the blazars in the Swift-BAT catalogue, we note that all the high-redshift blazars detected by both Fermi-LAT and Swift-BAT have \( L_\gamma > 2 \times 10^{48} \) erg s\(^{-1}\), suggesting that only the most luminous \( \gamma \)-ray blazars are detected by both instruments. Most of the LAT sources detected by BAT, including PKS 2149–306, have a soft \( \gamma \)-ray photon index \( \Gamma_\gamma > 2.5 \). This corresponds in hard X-rays to a photon index \( \Gamma_X < 1.6 \) (see Fig. 6). This result confirms that the detection of these high-redshift blazars strongly depends on the position of their IC peaks. According to the blazar sequence (Fossati et al. 1998), as the bolometric luminosity of a blazar increases the synchrotron and IC peak moves to lower frequencies. Considering that high-redshift FSRQ are powerful blazars with high bolometric luminosity, their IC peak is usually expected in the 1–10 MeV energy range, below the energy range covered by Fermi-LAT (see e.g. Tagliaferri et al. 2015). However, during strong flaring activity the IC peak may shift to higher energies as in the case of the 2013 flare from PKS 2149–306.

28 high-redshift blazars detected by Fermi-LAT have \( L_\gamma > 10^{48} \) erg s\(^{-1}\). The vast majority of them have a BH mass \( > 10^9 \) M\(_\odot\) (Ghisellini et al. 2009, 2010, 2011, 2014b), confirming that the most powerful blazars have the heaviest BH (Ghisellini et al. 2013). In particular, PKS 2149–306 has a BH mass of \( 3.5 \times 10^9 \) M\(_\odot\), as estimated by Tagliaferri et al. (2015).

### 6.2 X-ray properties

We investigated the X-ray properties of PKS 2149–306 by means of Swift-XRT, XMM–Newton, and NuSTAR observations. The X-ray spectrum collected by XMM–Newton in 2001 is quite well modelled by a simple PL with a photon index of \( \Gamma_X = 1.45 \pm 0.01 \) and a 0.3–10 keV flux of \( 7.9 \times 10^{-13} \) erg cm\(^{-2}\) s\(^{-1}\). During 2005 December–2014 April, Swift-XRT observed the source with a 0.3–10 keV flux in the range \( (1.2–2.8) \times 10^{-14} \) erg cm\(^{-2}\) s\(^{-1}\), with a photon index varying between 1.0 and 1.5. Fig. 7 shows the X-ray photon index estimated from Swift-XRT and XMM–Newton observations as a function of the X-ray flux in the 0.3–10 keV range: despite the large errors, a hint of hardening of the spectrum with the increase of the flux is observed.

Unfortunately the Swift observations did not cover the \( \gamma \)-ray flaring periods detected in 2011 February and 2013 January, preventing us from investigating the X-ray behaviour during these \( \gamma \)-ray flaring events.

The NuSTAR spectra collected in the 3–76 keV energy range during 2013 December 17 and 2014 April 18 are well fitted by a simple PL with photon index \( \Gamma_X = 1.37 \pm 0.01 \) and \( \Gamma_X = 1.46 \pm 0.01 \), respectively. The two simultaneous observations of PKS 2149–306 by Swift-XRT and NuSTAR showed that the broadband X-ray spectrum is well described by a broken PL model, with a very hard spectrum (\( \Gamma_1 \sim 1 \)) below the break energy, at \( E_{\text{break}} = 2.5–3.0 \) keV, and \( \Gamma_2 = 1.37 \pm 0.01 \) and \( 1.46 \pm 0.01 \) above the break energy. Swift-BAT and BeppoSAX observed a photon index \( \Gamma_X = 1.50 \pm 0.10 \) (Baumgartner et al. 2013) and \( \Gamma_X = 1.40 \pm 0.04 \) (Elvis et al. 2000) in the 14–195 keV and 20–200 keV energy range,
respectively, in agreement with the photon index $\Gamma_z$ obtained by the two Swift-XRT and NuSTAR joint fits. The 3–76 keV flux varied by about 40 per cent between the first and second NuSTAR observation. At the same time the 0.3–10 keV flux varied by less than 10 per cent. In the same way, the photon index below the break energy did not change, while the photon index above the break energy was harder when the source was brighter.

In several high-redshift ($z > 4$) blazars a steepening of the soft X-ray spectrum has been observed (e.g. Yuan et al. 2006, and references therein). This steepening may be due to either an excess of absorption in the soft X-ray part of the spectrum or due to an intrinsic curvature of the electron energy distribution responsible for the X-ray emission. In PKS 2149$-306$ this feature was observed below 3 keV, and an improvement of the fit is observed when an extra absorber at the redshift of the source ($N_H \sim \times 10^{22}$ cm$^{-2}$) is added to the simple PL model. However, this improvement is not as good as when we use a broken PL model. The AGN may be surrounded by a dense plasma in form of a wind or an outflow (e.g. Fabian 1999). This intervening material may be responsible for the extra absorption observed in high-redshift quasars (e.g. Vignali et al. 2005). However, in contrast to radio-loud quasars, it is unlikely that for a blazar like PKS 2149$-306$ such a large gas column density in the line of sight is not removed by the relativistic jet that should be well aligned with the line of sight. Moreover, with a hydrogen column density of about $10^{22}$ cm$^{-2}$ obtained by fitting the X-ray spectrum the corresponding optical obscuration (see e.g. Guver & Ozel 2009) would be very high ($A_V \sim 10$) and the source would not be detectable in optical–UV with the short exposures of the Swift observations. This problem may be solved by invoking a high-ionization state of the gas, but it is not possible to have conclusive evidence from its X-ray spectrum. In fact, due to the redshift of this source the most important spectral features used as a diagnostic are out of the energy range covered by Swift and XMM–Newton.

The most likely explanation of the steepening of the spectrum is that the soft X-ray emission is produced by external Compton radiation from the electrons at the lower end of the energy distribution (e.g. Tavecchio et al. 2007). This is in agreement with the stable photon index below 3 keV and the change of the photon index above $\sim 3$ keV, where the emission is produced by the most energetic electrons. In this context the lack of a clear steepening in the X-ray spectrum collected by XMM–Newton in 2001 may be related to the lower flux with respect to that estimated during the Swift-XRT and NuSTAR observations. The intrinsic curvature in soft X-rays would be less evident during the low activity of the source. The situation may be more complex due to the possible presence in the X-ray band also of the synchrotron self-Compton emission (SSC). However, the relative importance of the SSC component should decrease with the luminosity of the source (e.g. Ghisellini et al. 1998), and therefore should be negligible in powerful FSRQ such as PKS 2149$-306$. Moreover, Celotti et al. (2007) proposed the presence of a spectral component in X-rays produced by the Comptonization of ambient photons by cold electrons in the jet approaching the BLR. However, the direct detection of such a component has remained elusive. It is worth nothing that the broad-band spectrum of PKS 2149$-306$ including the Swift-XRT and NuSTAR data are better fitted by considering the emitting region outside the BLR (e.g. Tagliaferri et al. 2015), where the contribution of the bulk Comptonization should be negligible.

Considering the blazars included in the 70-month Swift BAT catalogue with a redshift $z > 2$, 7 out of 17 have not been detected by Fermi-LAT so far. Only sources with a $\Gamma_X < 1.6$ have been detected in $\gamma$ rays, while no dependence on the X-ray luminosity seems to be evident (Fig. 8). This is confirmed by the fact that the average photon index of the FSRQ detected by LAT, $< \Gamma_{LAT}^{X} > \sim 1.42 \pm 0.09$ is quite different from that of the sources detected by BAT and not by LAT, $< \Gamma_{LAT}^{X>3h} > \sim 1.85 \pm 0.17$. Seven blazars with $z > 3$ have been detected by Swift-BAT, and another one, IGR J12319$-0749$, by INTEGRAL-IBIS (Bassani et al. 2012). In addition, two blazars at redshift $z > 5$ have been detected by NuSTAR. Only two of these ten blazars have been detected by Fermi-LAT: PKS 0537$-286$ (e.g. Bottacini et al. 2010) and TXS 0800+618 (e.g. Ghisellini et al. 2010), confirming that the $\gamma$-ray energy range is not ideal for detecting blazars at redshift $> 3$. Among the FSRQ detected by both BAT and LAT, PKS 2149$-306$ is the third most luminous after PKS 1830$-211$ (e.g. Abdo et al. 2015) and B2 0743+25 (e.g. Ghisellini et al. 2010).

6.3 Optical and UV properties

In powerful high-redshift blazars, such as PKS 2149$-306$, the synchrotron peak is shifted to the mm-regime, leaving the thermal emission from the accretion disc as the dominant contribution in the optical–UV part of the spectrum (e.g. Tagliaferri et al. 2015). This accretion disc emission is not expected to vary on short timescales. During 2005–2014, the difference between the maximum and minimum magnitude observed by Swift-UVOT is 0.6, 0.7, 1.1, 0.8, 0.6, and 0.6 mag (corresponding to a variation of the flux density of 1.5, 1.8, 2.8, 2, 1.5, 1.5) from the $v$ to the $w2$ band. No significant variability was observed on a time-scale of a few days, in agreement with thermal emission from an accretion disc.

7 SUMMARY

In this paper, we discussed the $\gamma$-ray and X-ray properties of the high-redshift FSRQ PKS 2149$-306$ by means of Fermi-LAT, NuSTAR, XMM–Newton, and Swift data. We summarize our main conclusions as follows.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure8.png}
\caption{X-ray photon index versus X-ray apparent isotropic luminosity in the 14–195 keV energy range for the blazars with $z > 2$ detected by Swift-BAT. The filled and open triangles represent the objects detected and not detected by Fermi-LAT, respectively. The star represents PKS 2149$-306$.}
\end{figure}
(i) PKS 2149–306 showed a significant increase in its γ-ray activity in 2011 February and 2013 January. During the 2013 flare the flux increase was accompanied by a significant change of the spectral slope, not observed during the 2011 flare.

(ii) During the 2013 γ-ray flaring activity significant flux variations are observed on a 6-h time-scale, compatible with the light crossing time of the event horizon of the SMBH. On 2013 January 20, the source reached a daily γ-ray peak flux of \((301 \pm 36) \times 10^{-8} \text{ph cm}^{-2} \text{s}^{-1}\), up to \((385 \pm 70) \times 10^{-8} \text{ph cm}^{-2} \text{s}^{-1}\) on a 6-h time-scale. These values correspond to an apparent isotropic γ-ray luminosity of \((1.5 \pm 0.2) \times 10^{49}\) and \((1.9 \pm 0.3) \times 10^{49} \text{erg s}^{-1}\), respectively, comparable to the highest values observed from FSRQ up to now.

(iii) The average γ-ray luminosity of PKS 2149–306 over 6 yr of Fermi operation is \(4.4 \times 10^{48} \text{erg s}^{-1}\). This is the third brightest blazar with \(z > 2\) detected by LAT, after PKS 1830–211 and PKS 0537–286.

(iv) All high-redshift blazars detected by both Fermi-LAT and Swift-BAT have an \(L_{\gamma} > 2 \times 10^{36} \text{erg s}^{-1}\), suggesting that only the most luminous γ-ray blazars are detected by both instruments. Like most of the LAT blazars detected by BAT, PKS 2149–306 has a soft γ-ray photon index \(\Gamma_{\gamma} > 2.5\). This corresponds to a photon index \(\Gamma_{x} < 1.6\) in hard X-rays.

(v) Among the FSRQ with \(z > 2\) detected by both BAT and LAT, PKS 2149–306 is the third most luminous in hard X-rays after PKS 1830–211 and B2 0743+25.

(vi) The broad-band X-ray spectrum of PKS 2149–306 observed by Swift-XRT and NuSTAR is well described by a broken PL model, with a very hard spectrum \((\Gamma_{\gamma} \sim 1)\) below the break energy, at \(E_{\text{break}} = 2.5–3.0 \text{keV}\), and \(\Gamma_{\gamma} \sim 1.4–1.5\) above the break energy.

(vii) The steepening of the spectrum below \(\sim 3 \text{keV}\) could be due to the fact that the soft X-ray emission is produced by the low-energy tail of the relativistic electrons producing IC emission. This is in agreement with the small variability amplitude and the lack of spectral changes observed in that part of the X-ray spectrum between the two NuSTAR and Swift joint observations. An extra absorption due to material surrounding the SMBH is unlikely because the relativistic jet should efficiently remove the gas along the line of sight. Moreover, this extra absorption should correspond to a very large extinction in optical and UV, in contrast to the detection of the source by Swift-UVOT.

(viii) Fermi-LAT and Swift-BAT observations are confirming that the hard X-ray band is more effective in selecting bright FSRQ at \(z > 3\) (see e.g. Ghisellini et al. 2010; Ajello et al. 2012), while the γ-ray band is very effective up to \(z = 2\) (see e.g. Ackermann et al. 2015).

Further multiwavelength observations of PKS 2149–306 will be important for shedding light on the properties of high-\(z\) blazars. In particular, simultaneous optical-to-X-ray observations during a γ-ray flaring activity will allow us to compare its broad-band spectral energy distribution between both low and high activity states, constraining the emission mechanisms at work.

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