New Astronomy 44 (2016) 21–28

Contents lists available at ScienceDirect

New Astronomy

journal homepage: www.elsevier.com/locate/newast

Flux and spectral variability of the blazar PKS 2155−304 with XMM–Newton: Evidence of particle acceleration and synchrotron cooling

Jai Bhagwan[a,b], A.C. Gupta[a,*], I.E. Papadakis[c,d], Paul J. Wiita[e]

[a] Aryabhatta Research Institute of Observational Sciences (ARIES), Manora Peak, Nainital 263002, India
[b] School of Studies in Physics and Astrophysics, Pt. Ravishankar Shukla University, Amanaka G.E. Road, Raipur 492010, India
[c] Department of Physics and Institute of Theoretical and Computational Physics, University of Crete, GR-71003 Heraklion, Greece
[d] ESL, Foundation for Research and Technology, Heraklion 71110, Greece
[e] Department of Physics, The College of New Jersey, PO Box 7718, Ewing, NJ 08628-0718, USA

A R T I C L E I N F O

Article history:
Received 11 May 2015
Revised 18 August 2015
Accepted 31 August 2015
Available online 8 September 2015

Communicated by F.D. Macchetto

Keywords:
Blazars: PKS 2155−304
XMM–Newton telescope: X-ray observations

A B S T R A C T

We have analyzed *XMM–Newton* observations of the high energy peaked blazar, PKS 2155−304, made on 24 May 2002 in the 0.3–10 keV X-ray band. These observations display a mini–flare, a nearly constant flux period and a strong flux increase. We performed a time-resolved spectral study of the data, by dividing the data into eight segments. We fitted the data with a power-law and a broken power-law model, and in some of the segments we found a noticeable spectral flattening of the source's spectrum below 10 keV. We also performed "time-resolved" cross-correlation analyses and detected significant hard and soft lags (for the first time in a single observation of this source) during the first and last parts of the observation, respectively. Our analysis of the spectra, the variations of photon-index with flux as well as the correlation and lags between the harder and softer X-ray bands indicate that both the particle acceleration and synchrotron cooling processes make an important contribution to the emission from this blazar. The hard lags indicate a variable acceleration process. We also estimated the magnetic field value using the soft lags. The value of the magnetic field is consistent with the values derived from the broad-band SED modeling of this source.

1. Introduction

The blazar subclass of radio-loud active galactic nuclei (AGN) includes BL Lacertae objects (BL Lacs) and flat spectrum radio quasars (FSRQs). Blazars display large amplitude flux and polarization variability on all possible timescales ranging from a few tens of minutes to many years across the entire electromagnetic (EM) spectrum (Ulrich et al., 1997). Blazar's center is a super massive black hole that accretes matter and produces relativistic jets pointing almost in the direction of our line of sight (Urry and Padovani, 1995). The emission from blazars is predominantly nonthermal. The spectral energy distributions (SEDs) of blazars have two humps in the log(νF_ν) vs log(ν) representation (Ghisellini, 1997). Based on the location of the low frequency hump, blazars are sub-classified into three categories: LSPs (low synchrotron peak), ISPs (intermediate synchrotron peak), and HSPs (high synchrotron peak) blazars (Abdo, 2010). The low energy SED hump peaks from sub-mm to soft X-ray bands and is well explained by synchrotron emission from an ultra-relativistic electron population residing in the magnetic fields of the approaching relativistic jet (Maraschi et al., 1992; Ghisellini, 1993; Hovatta, 2009). The high energy SED hump that peaks in the MeV–TeV gamma-ray bands is not as well understood but is usually believed to be attributed to inverse Compton (IC) scattering of photons off those relativistic electrons.

Variability in blazars on timescales of a few minutes to less than a day often is known as intra-day variability (IDV) (Wagner and Witzel, 1995); variability timescales from days to several weeks is sometimes called short timescale variability (STV), while variability on month to year timescales is known as long term variability (LTV) (Gupta, 2004).

X-ray variability in HBLs is characterized by correlated changes of the spectral index with the X-ray flux and lags between soft and hard X-rays. A photon index-flux correlation was first observed by George et al. (1988) in Mrk 421 using *EXOSAT*. Similar results were also obtained for other HBLs (Giommi, 1990; Sambruna, 1994). A soft lag in the HBL H 0323+022 in *Ginga* X-ray observations was observed for the first time by Kohmura (1994).

PKS 2155−304 ($\alpha_{2000.0}$ = 21h 58m 52.0s, $\delta_{2000.0} = -30^\circ\ 13'\ 32''$) at $z = 0.116$ is a HSP blazar that is highly variable across the

* Corresponding author. Tel.: +91 9936683176; fax: +91 5942 233439.
E-mail address: acgupta30@gmail.com (A.C. Gupta).

http://dx.doi.org/10.1016/j.newast.2015.08.005
1384-1076/

entire EM spectrum Gaur (2010). It is the brightest blazar in the UV to $\gamma-$ray bands in the southern hemisphere. Blazar variability is best studied throughout different phases which can be considered to be: outburst, pre/post outburst, and low states. PKS 2155-304 is one of the most commonly observed blazars for simultaneous multi-wavelength observations and has received maximum attention for simultaneous multi-wavelength campaigns (Carini and Miller, 1992; Urry, 1993; 1997; Brinkmann, 1994; Courvoisier, 1995; Edelson, 1995; Pesce, 1997; Pian, 1997; Marshall, 2001; Aharonian, 2005; 2009a; Dominici et al., 2006; Zhang, 2005; 2006; Dolcini, 2007; Piner et al., 2008; Sakamoto, 2008; Kapanadze, 2014; Collaboration, 2012). This blazar has also been observed in assorted single EM bands over more diverse timescales. For instance, (Kastendieck et al., 2011) have studied the long term optical variability of this source while (Gaur, 2010) have studied the X-ray IDV in the blazar. There is some evidence for PKS 2155−304 having shown quasi-periodic oscillations (QPOs) on IDV time scales from *IUE* and *XMM–Newton* observations (Gaur, 2010; Urry, 1993; Lachowicz, 2009). (Morini, 1986; Sembay, 1993) observed PKS 2155−304 in the high flux state and detected pronounced spectral variations. Using *XMM–Newton* data (Zhang, 2008) have reported that the synchrotron emission of PKS 2155−304 then peaked in UV−EUV bands rather then the soft X-ray band. Massaro (2008) fitted the SED of PKS 2155−304 with a log-parabolic model and found that the curvature of the SED is anti-correlated with the peak energy E_p.

In a recent paper (Bhagwan, 2014), we used all the archival XMM/Newton observations of PKS 2155-304 in order to study its broad band (optical/UV/X–rays) flux and spectral variability. We found that the long term optical/UV and X-ray flux variations in this source are mainly driven by model normalization variations. We also found that the X-ray band flux is affected by spectral variations. Overall, the energy at which the emitted power is maximum correlates positively with the total flux. As the spectrum shifts to higher frequencies, the spectral 'curvature' increases as well, in contrast to what is expected if a single log-parabolic model were an acceptable representation of the broad band SEDs. These results suggested that the optical/UV and X-ray emissions in this source may arise from different lepton populations.

We have now started the study of the individual XMM/Newton observations of the same source, with the aim to study its short term X–ray variability properties, since these data provide an excellent opportunity to analyze and model the blazar emission in different flux states with identical instrumentation. In this paper, we present the results from the analysis of the XMM/Newton observation of PKS 2155-304 which was taken on 24 May 2002. The same data have been analyzed by Zhang (2005, 2006). They have studied the short term variability and cross correlation analysis between the different X-ray energy bands. The observation includes three nearly equal length pointings at the blazar with a total exposure time of 93 ks. But each exposure has been taken with different filters. We noticed that the combined light curve of these three pointings shows nearly stable flux states, declining flux states, rapid flares, and weak oscillations. We have found evidence for flux related spectral variations (which is typical of this source), but we also find evidence (for first time) for the presence of both "hard" and "soft" time lags, which are variable with time. Since the flux variability behavior in this observation is rather typical of the source, we believe that the results we present in this paper may be representative of the X–ray variability properties of the source. This will be confirmed when we will have finished the analysis of the remaining observations as well. The final results will hopefully offer us a more complete view on the physical processes which dominate the X-ray flux and spectral evolution in the source.

The paper is structured as follows. In section 2, we present the data and our reduction procedure. In section 3 we report the results, and in section 4 we discuss them in the context of acceleration and/or cooling processes that may operate in the system, and we present our summary.

2. Data and reduction

We analyzed the archival XMM–Newton EPIC/pn data of the blazar PKS 2155-304 in the 0.3–10 keV X-ray band. These observations were made on 24 May 2002 (orbit 450, Obs ID 0124930501; PI: Fred Jansen). This observation ID has three continuous EPIC/pn exposures in small window (SW) mode with different filters: 450–1 was taken in the medium filter, 450–2 in the thin filter and 450–3 in the thick filter. The duration of the respective cleaned files are 31.7, 31.6 and 29.7 ks, respectively. The Original Data File (ODF) was reprocessed using Science Analysis System (SAS) version 11.0.0 with the most recent available calibration files.

By generating a hard band background light curve in the energy range 10–12 keV, we have checked for the high soft proton background periods which are caused by solar activity. We removed those points for which the hard band count rate was greater than 0.4 count/sec, and then we generated the good time interval (GTI) data. We have used the single and double events with quality and pattern flags constrained to $(FLAG = 0)\&(PATTERN \leq 4)$ for our analysis. We have carefully examined the pile-up effect in the data by SAS task *epatplot* and found that the data is indeed affected by pile-up. As a result, we extracted the source count from an annuls region which was centered on the source with inner radius of $10''$ and outer radius of $40''$. The background counts were accumulated from a circular region of radius $45''$ on the CCD chip near where the source was located and least affected from the source counts.

We extracted background subtracted light curves by using the *epiclccorr* command. The spectral analysis was done by using the *xmmselect* and *specgroup* tasks in SAS. We have used the task *specgroup* to rebin all spectra, in order to have at least 50 counts for each background subtracted spectral channel and the value of over sampling parameter is taken as 5.

3. Results

3.1. Light curves

We present the light curves extracted from entire observation of PKS 2155−304 in the five energy bands of 0.3–0.5, 0.5–2.0, 2.0–4.0, 4.0–10.0 and 0.3–10.0 keV (with an 100 s binning) in Fig. 1. As mentioned above, this observation consists of three exposures with a duration 31.7, 31.6 and 29.7 ks, respectively. The gaps between the individual exposures are of the order of $\sim$1.5 ks. The three sub-parts are easily spotted by the abrupt change in the source flux. For example, the flux drop at around $\sim$65 ks since the start of the observation is not real, but is due to the change of the EPIC/pn filters, since the EPIC/pn thin filter is more transparent to the soft energy photons than the thick filter. A similar effect, but of a much smaller amplitude, is observed $\sim$30 ks since the start of the observation, when the EPIC/pn filter was switched from medium to thin.

Despite the EPIC/pn filter changes, a visual inspection indicates significant and clearly defined flux variability in the light curve. In Fig. 1, the individual exposures are marked as segments 1, 2, and 3. We divided segment 1 into three sub-segments: 1(a) where the source flux is almost constant; 1(b) where the flux decreases; and 1(c) where the source flux rises. Segment 2 is relatively flat, but this is when the source has shown a hint of a QPO (Gaur, 2010). Segment 3 is divided into four sub-segments: 3(a), with decreasing flux, 3(d) corresponds to the $\sim$ constant flux level towards the end of the observation, while 3(b) and 3(c) are defined during the first and second part of the strong rising flux state in between. The percentage variability and signal to noise ratio (S/N) of segment 1–3 in 0.3–10.0 keV band are 6.6 ± 0.16, 1.5 ± 0.22, 21 ± 0.15 and 37.7, 39.3, 38.0, respectively.