X-ray Intraday Variability of HBL Blazars with XMM-Newton

P. U. Devanand,1 Alok C. Gupta,1 V. Jithesh,2,1 and Paul J. Wiita3

1 Aryabhata Research Institute of Observational Sciences (ARIES), Manora Peak, Nainital 263001, India
2 Department of Physics and Electronics, CHRIST (Deemed to be University), Hosur Main Road, Bengaluru - 560029, India
3 Department of Physics, The College of New Jersey, 2000 Pennington Rd., Ewing, NJ 08628, USA

ABSTRACT

We present an extensive study on the X-ray intraday variability of ten TeV-emitting high synchrotron peaked blazars (HBLs): 1ES 0229+200, 1ES 0414+009, PKS 0548-322, 1ES 1101-232, 1H 1219+301, H 1426+428, Mrk 501, 1ES 1959+650, PKS 2005-489, and 1ES 2344+514 made with twenty-five XMM-Newton pointed observations during its operational period. Intraday variability has been estimated in three energy bands: soft (0.3–2 keV), hard (2–10 keV) and total (0.3–10 keV). Although seven out of these ten TeV HBLs exhibited some intraday variability at three-sigma levels no major variations exceeding six percent were detected. We explored the spectral properties of the sample by extracting the hardness ratio from the soft and hard bands; no significant variations in the hardness ratio were observed in any source. We performed power spectral density analyses on the variable light-curves by fitting power-laws, yielding slopes lying in the range from 1.11 to 2.93 for different HBLs. We briefly discuss possible emission mechanisms and carry out rough estimates for magnetic fields, electron Lorentz factors and emission region sizes for seven of these HBLs.

Keywords: general - HBL blazars: Individual (1ES 0229+200, 1ES 0414+009, PKS 0548-322, 1ES 1101-232, 1H 1219+301, H 1426+428, Mrk 501, 1ES 1959+650, PKS 2005-489, 1ES 2344+514)

1. INTRODUCTION

Active galactic nuclei (AGN) are the central regions of certain galaxies, which emit enormous amounts of energy across the entire electromagnetic (EM) spectrum that usually outshine all the stars in their host galaxies. AGNs are universally believed to be powered by accreting supermassive black holes (SMBH; \(10^6 - 10^{10} \, M_{\odot}\)), lying at their centers (Rees 1984). About 10–15% of AGNs clearly include well collimated jets of relativistic particles and these jetted AGNs emit significant radio emission (Padovani et al. 2017). These relativistic jets are particularly luminous at radio and \(\gamma\)-ray frequencies.

Types of jetted-AGN are distinguished by the angle of the jet with respect to the viewer’s line of sight, with blazars being those in which one of their relativistic jets is aligned at a small angle (\(\lesssim 15^\circ\) to the observer; Urry & Padovani 1995). Blazars have historically been classified into two categories: BL Lacertae (BL Lac) objects, which have nearly featureless spectra or very weak emission lines (equivalent width \(\lesssim 5\AA\); Stocke et al. 1991; Marcha et al. 1996), and flat spectrum radio quasars (FSRQs), which have broad and strong emissions lines in their composite optical/UV spectra (Blandford & Rees 1978; Ghisellini et al. 1997). Some weaker AGN, particularly Narrow Line Seyfert 1 galaxies, also have relativistic jets pointing close to our line of sight (Foschini 2020). Blazars exhibit flux and spectral variability across all accessible EM bands. The observed emission, which is predominantly non-thermal, is dominated by Doppler boosted radiation from relativistic jets. Other outstanding characteristics of blazars are their core-dominated radio structures and strong polarization in radio and optical bands.

The multi-wavelength spectral energy distribution (SED) of blazars is characterized by a double-humped structure (e.g. Fossati et al. 2008). Synchrotron emission from relativistic electrons gyrating around the magnetic field in relativistic jets produces the low-energy hump which peaks somewhere between IR and X-ray band. A recent examination of a large sample of jetted AGN (Keenan et al. 2021) has shown that the claimed anti-correlation between synchrotron peak frequency and peak luminosity, called the blazar sequence, is not significant. It appears to be preferable to classify these AGN by whether their jets are associated with efficient...
accretion (strong, ‘quasar-mode’, or Type II jets) or inefficient accretion (weak, Type I jets; Keenan et al. 2021).

The physical mechanisms responsible for the high-energy hump, which peaks in GeV-TeV energies, can be broadly separated into leptonic and hadronic models. In leptonic models the high energy hump is due to inverse-Compton (IC) scattering of either low energy synchrotron photons (Synchrotron Self-Compton (SSC); e.g. Bloom & Marscher 1996) or low energy external photons (External Compton, EC; e.g. Blandford & Levinson 1995) by the same electrons in relativistic jets which are responsible for the synchrotron emission. In hadronic models, the high energy hump is due to synchrotron emission from relativistic protons and/or proton-photon cascade processes. On the basis of their peak synchrotron frequency ($\nu_s$), BL Lacs were classified as low energy peaked BL Lacs (LBLs), intermediate energy peaked BL Lacs (IBLs), and high energy peaked BL Lacs (HBLs). This classification was later modified to include FSRQs by Abdo et al. (2010), giving us low synchrotron peaked blazars (LSPs; $\nu_s < 10^{14}$Hz), intermediate synchrotron peaked blazars (ISPs; $10^{14}$Hz < $\nu_s < 10^{15}$Hz) and high synchrotron peaked blazars (HSPs; $\nu_s > 10^{15}$Hz).

Blazars exhibit flux variation across entire EM spectrum in diverse timescales down to timescales of hours or even a few minutes. Flux variations lasting from a few minutes to less than a day are termed as intra-day variability (IDV; e.g. Wagner & Witzel 1995) or intra-night variability (e.g. Goyal et al. 2009) or micro-variability (e.g. Miller et al. 1989). Variations in flux on timescales from days to a few weeks to even a few months are termed as short-term variability (STV), while flux variations seen over greater timespans are termed as long-term variability (LTV; e.g. Gupta et al. 2004). Over the last decade, we have studied the IDV of blazars in X-ray bands by utilizing timing data from various X-ray telescopes: Chandra (Aggrawal et al. 2018), NuSTAR (Pandey et al. 2017, 2018), Suzaku (Zhang et al. 2019, 2021), and XMM-Newton (Gaur et al. 2010; Kalita et al. 2015; Bhagwan et al. 2016; Gupta et al. 2016; Wani & Gaur 2020; Dhiman et al. 2021).

BL Lac objects are expected to be best candidates for TeV emission among blazars. This is based on the assumption that there is much less TeV absorbing material in the vicinity of their emission regions as their optical spectra contain essentially no emission lines (e.g. Dermer & Schlickeiser 1994). The terminology “high-frequency-peaked BL Lac objects (HBLs)” was introduced by Padovani & Giommi (1995) to describe BL Lac objects in which the lower energy hump peaks in the X-ray range. There were only six TeV HBLs (Markarian 421, H 1426+428, Markarian 501, 1ES 1959+650, PKS 2155-304 and 1ES 2344+514) known until 2005. The Fermi satellite and several ground-based very-high energy (VHE) $\gamma$-ray facilities such as the High Energy Spectroscopic System (HESS), the Major Atmospheric Gamma-ray Imaging Cherenkov telescopes (MAGIC), and the Very Energetic Radiation Imaging Telescope Array System (VERITAS), discovered a substantial number of HBLs in the last 17 years and revolutionized $\gamma$-ray blazar astronomy. At the time of writing this paper, the total number of blazars in the TeV source catalogue\(^1\) (TeVcat) is comprised of 55 HBLs, 10 IBLs, 2 LBLs, 9 FSRQs, and 4 blazars and 2 BL Lacs with unclear classifications.

X-ray IDV for blazars is an intrinsic phenomenon and may be related to some activity in the innermost region near the central SMBH. IDV timescale studies can help in constraining the size of the emitting region and in estimating a crude mass of the central SMBH. Our main motivation for this work is to understand X-ray variability properties on IDV-timescales of HBLs that show emission at highest energies.

The paper is arranged as follows: Section 2 shortly describes the XMM-Newton satellite instrumentation, the archival data of HBLs we selected and our reduction methodology. Various analysis techniques we used to study flux and spectral variations are discussed in section 3. Results and associated discussion are presented in section 4 and 5, respectively. We report our conclusions in section 6.

2. INSTRUMENTATION, DATA SELECTION, AND DATA REDUCTION

2.1. Instrumentation

The X-ray Multi-Mirror Newton (XMM-Newton) mission is a space observatory launched by the European Space Agency on 1999 December 10 and was, for the first time, capable of performing simultaneous imaging of sources in X-ray and optical (visible & UV) bands (Mason et al. 2001). It was placed in a 48-hour elliptical orbit at 40° inclination to the equator and car-

\(^1\) http://tevcat.uchicago.edu/
### Table 1. Observation log for XMM-Newton data

| Source      | α_{2000.0} | δ_{2000.0} | z     | Obs Date   | Obs ID    | Window | Pile-up | Exposure | Good Exp | Bin Size |
|-------------|------------|------------|-------|------------|-----------|--------|---------|----------|----------|----------|
|             | hh mm ss.ss | dd mm ss.ss |       |            |           |        |         |          |          |          |
| 1ES 0229+200 | 02 32 48.61 | +20 17 17.49 | 0.1400 | 2009 Aug 21 | 0604210201 | Full   | No      | 23.61    | 17.30    | 100      |
|             |            |            |       | 2009 Aug 23 | 0604210301 | Full   | No      | 27.71    | 21.20    | 100      |
| 1ES 0414+009 | 04 16 52.49 | +01 05 23.89 | 0.2870 | 2002 Aug 26 | 0094383101 | Small  | No      | 10.96    | 10.40    | 100      |
|             |            |            |       | 2003 Sep 01 | 0161160101 | Small  | No      | 79.36    | 71.60    | 300      |
| PKS 0548-322 | 05 50 40.57 | -32 16 16.49 | 0.0690 | 2002 Oct 19 | 0142270101 | Full   | Yes     | 94.50    | 80.00    | 400      |
|             |            |            |       | 2004 Oct 19 | 0205920501 | Timing | No      | 40.92    | 24.90    | 100      |
| 1ES 1101-232 | 11 03 37.62 | -23 29 31.20 | 0.1860 | 2009 Aug 23 | 0205920601 | Timing | No      | 18.50    | 17.30    | 100      |
| 1H 1219+301  | 12 21 21.94 | +30 10 37.16 | 0.1836 | 2001 Jun 11 | 0111840101 | Small  | No      | 29.94    | 28.40    | 200      |
| H 1426+428   | 14 28 32.61 | +42 40 21.05 | 0.1293 | 2001 Jun 16 | 0111850201 | Small  | No      | 68.57    | 52.80    | 300      |
|             |            |            |       | 2004 Aug 04 | 0165770101 | Small  | No      | 67.87    | 56.10    | 300      |
|             |            |            |       | 2004 Aug 06 | 0165770201 | Small  | No      | 68.92    | 60.30    | 300      |
|             |            |            |       | 2005 Jan 24 | 0212090201 | Small  | No      | 30.41    | 28.80    | 200      |
|             |            |            |       | 2005 Jul 19 | 0310190101 | Small   | Yes     | 47.03    | 33.40    | 200      |
|             |            |            |       | 2005 Jun 25 | 0310190201 | Small   | No      | 49.50    | 40.20    | 200      |
|             |            |            |       | 2005 Aug 04 | 0310190501 | Small   | Yes     | 47.54    | 35.20    | 200      |
| Mrk 501     | 16 53 52.22 | +39 45 36.61 | 0.0330 | 2010 Sep 08 | 0652570101 | Small  | No      | 44.91    | 39.80    | 200      |
|             |            |            |       | 2010 Sep 10 | 0652570201 | Small  | No      | 44.92    | 44.80    | 200      |
|             |            |            |       | 2011 Feb 11 | 0652570301 | Small  | No      | 40.91    | 40.80    | 200      |
|             |            |            |       | 2011 Feb 15 | 0652570401 | Small  | No      | 40.72    | 40.20    | 200      |
| 1ES 1959+650 | 19 59 59.85 | +65 08 54.65 | 0.0470 | 2019 Jul 05 | 0850980101 | Small  | Yes     | 44.00    | 38.00    | 200      |
|             |            |            |       | 2020 Jul 16 | 0870210101 | Small   | Yes     | 33.10    | 31.40    | 200      |
| PKS 2005-489 | 20 09 25.34 | -48 49 53.72 | 0.0707 | 2004 Oct 04 | 0205920401 | Timing | No      | 12.92    | 11.70    | 100      |
|             |            |            |       | 2005 Sep 26 | 0304080301 | Timing  | No      | 27.92    | 14.60    | 100      |
|             |            |            |       | 2005 Sep 28 | 0304080401 | Timing  | No      | 27.92    | 24.10    | 200      |
| 1ES 2344+514 | 23 47 04.84 | +51 42 17.88 | 0.0440 | 2020 Jul 22 | 0870400101 | Small  | No      | 28.90    | 26.80    | 200      |

Note—Right Ascension (α_{2000.0}), Declination (δ_{2000.0}) and red-shift (z) are taken from the Simbad astronomical database (http://simbad.u-strasbg.fr/simbad/).

Handbook 2021\(^2\), XMM-Newton Calibration Technical Note\(^3\). In our study we have considered only EPIC-PN data as it is more sensitive and less effected by photon pile-up effects (Turner et al. 2001).

#### 2.2. Data Selection Criteria

Among the 55 HBLs in TeVcat, 19 have been observed by XMM-Newton since its launch until March 2022. Of these, we excluded four of the sources previously studied by members of the group (e.g Mrk 421; Priyana

\(^2\)https://xmm-tools.cosmos.esa.int/external/xmm_user_support/documentation/uhb/

\(^3\)https://xmmweb.esac.esa.int/docs/documents/CAL-TN-0018.pdf
Noel et al. (2022), PKS 2155-304; Bhagwan et al. (2014, 2016), H 2356-309; Wani & Gaur (2020) and PG 1533+113; Dhiman et al. (2021)). We also did not analyze the shorter observations with exposure time less than 10 ks and those longer observations effected heavily by background flaring such that the good exposure time is below 10 ks. Sources IES 0033+595, IES 0347-121, IES 0647+250, Mrk 180 and TXS 1515-273 were excluded due to this reason. In addition, some observations were ignored, where the source fell between CCDs or where source was not detected at all.

Applying our selection criteria, we were left with 10 HBLs (1ES 0299+200, 1ES 0414+009, PKS 0548-322, 1ES 1101-232, 1H 1219+301, H 1426+428, Mrk 501, IES 1959+650, PKS 2005-489, and IES 2344+514) that involved 25 pointed observations of XMM-Newton. The X-ray data of these HBLs taken by EPIC was downloaded from the XMM-Newton public archive. The observation log is provided in Table 1, which contains the name of each source, its position and red-shift, date of observation, observation ID, window mode of observation, whether there was pile-up, exposure time, good exposure time, and the size of the temporal bin we used to produce X-ray light curves (LCs).

2.3. Data Reduction

EPIC-PN takes extremely sensitive images of X-ray sources in the energy range 0.15–15 keV (Turner et al. 2001). However, soft proton flaring often dominates over 10 keV so we restrict our analysis to the 0.3–10 keV energy range. Observation Data Files (ODF) were reprocessed using the standard procedure of the XMM-Newton Science Analysis System (SAS) version 19.1.0 with the help of updated Calibration Current Files. SAS task epproc was used to produce calibrated and concatenated EPIC-PN event lists from uncalibrated event lists. In order to create clean event lists, we search for soft proton flares by examining LCs in the 10–12 keV range. We then use SAS task tabtigen to generate a Good Time Interval (GTI) file, which contains information about proton flare free timings. Next we employ SAS task eve select, which uses GTI and uncalibrated event files as input to produce cleaned event files. Finally, SAS task epatplot is used to detect pile-up, if and it is eliminated by removing a small region from the center of the source and thus provides an annular region from which we extract the source events.

Out of these 25 observations, three were in full window imaging mode, five were in timing mode and the rest were in small window imaging mode. In imaging mode, source events are extracted using a circular aperture having 40′′ radius and background events are extracted using the same circular aperture but placed far away from the source. One observation of PKS 0548-322 (0142270101) and two observations each of H 1426+428 (0310190101, 0310190501) and IES 1959+650 (0850980101, 0870210101) were affected by pile-up. In those cases we have discarded the central portion around source and selected an annular region between 4′′ and 40′′ for extraction. In timing mode, source events are extracted from a 82′′ (RAW X=27–47) wide box along RAWX centred on the source’s vertical strip. Background events are extracted similarly from a box of 41′′ (RAWX=3–13) width from a source free region.

We obtained LCs that are background and vignetting corrected using SAS task epiclecorr. High background flaring if detected at beginning or/and at the end of a LC were completely removed. However, when short periods of high background flaring were detected in middle of a LC, we removed these points if they are fewer than five in number and used Lagrange’s interpolation method to replace the removed ones, as in González-Martín & Vaughan (2012). We defined the resultant continuous time interval obtained by following the above method as good exposure time. LCs with good exposure times above 10, 25, 50 and 75 ks were binned into segments of 100, 200, 300 and 400 s, respectively. Mean counts of the light curves obtained in this fashion in the soft (0.3–2.0 keV), hard (2.0–10.0 keV) and total (0.3–10.0 keV) energy bands are given in Table 2.

3. ANALYSIS TECHNIQUES

In this section, we discuss the techniques that we have used to analyze our data. The results we obtained by these techniques are discussed in section 4.

3.1. Excess Variance and Fractional Variance

We calculated excess variance $\sigma_{XS}^2$ and fractional variance $F_{\text{var}}$ (e.g Edelson et al. 2002), which are the parameters commonly used to quantify the strength of X-ray variability. Due to measurement errors in the observation, finite uncertainties will be present in the LC. These uncertainties will cause an additional variance on individual flux measurements. Excess variance, a measure of the intrinsic variance of a source, removes this additional variance arising from measurement errors. Suppose a LC consists of $N$ data points $x_j$ corresponding to times $t_j$ having associated measurement errors $\sigma_{\text{err},j}$,

https://nxsa.esac.esa.int/nxsa-web/
X-ray intraday variability of HBLs

then the excess variance is given by following expression

$$\sigma^2_{XS} = S^2 - \sigma^2_{err}. \quad (1)$$

Here $S^2$ is the sample variance of the LC, given by

$$S^2 = \frac{1}{N-1} \sum_{j=1}^{N} (x_j - \bar{x})^2, \quad (2)$$

and $\sigma^2_{err}$ is the mean square error of uncertainties, given by

$$\sigma^2_{err} = \frac{1}{N} \sum_{j=1}^{N} \sigma^2_{err,j}. \quad (3)$$

The fractional rms variability amplitude, $F_{var}$, is the square root of normalized excess variance $\sigma^2_{XS} = \sigma^2_{XS}/\bar{x}^2$ (e.g., Vaughan et al. 2003) and is given by,

$$F_{var} = \sqrt{S^2 - \frac{\sigma^2_{err}}{\bar{x}}}. \quad (4)$$

The uncertainty associated with $F_{var}$ (e.g., Vaughan et al. 2003) is given by,

$$(F_{var})_{err} = \sqrt{\left(\sqrt{\frac{1}{2N \bar{x}^2 F_{var}}}\right)^2 + \left(\frac{\sigma^2_{err}}{N \bar{x}}\right)}^2. \quad (5)$$

We consider a LC to be variable when $F_{var} > 3 \times (F_{var})_{err}$, following Dhiman et al. (2021).

### 3.2. Variability timescale

We determine the flux variability timescale following the method described in Bhatta et al. (2018), where it is given by (Burbidge et al. 1974)

$$\tau_{var} = \left| \frac{\Delta t}{\Delta \ln F} \right|. \quad (6)$$

Here $\Delta t$ is time interval between measured flux values $F_1$ and $F_2$, with $F_1 > F_2$ since $\Delta \ln F = \ln F_1 - \ln F_2$. As described in Hagen-Thorn et al. (2008), we calculated all possible pairs of timescale $\tau_{ij}$ which satisfy the condition $|F_i - F_j| > \Delta F_i + \Delta F_j$, where $\Delta F$ is the error associated with flux measurement. The shortest variability timescale is minimum of all such pairs $\tau = \min(\tau_{ij})$, where $i = 1, 2, ..., N - 1, j = i, i + 1, ..., N$, and $N$ is the number of flux values. The uncertainty in $\tau_{var}$ is given by (Bhatta et al. 2018)

$$\Delta \tau_{var} \approx \sqrt{\frac{F_1^2 \Delta F_2^2 + F_2^2 \Delta F_1^2}{F_1^2 F_2^2 [\ln(F_1/F_2)]^4}} \Delta t. \quad (7)$$

### Figure 1.

XMM-Newton LCs for 1H 1219+301 (Obs ID: 0111840101) and Mrk 501 (Obs ID: 0652570101) in the total energy range (0.3–10 keV).

### Figure 2.

Soft (0.3–2 keV; denoted by blue filled circles) and hard (2–10 keV; denoted by red filled circles) LCs for 1H 1219+301 and Mrk 501. The observations used here are same as that of Figure 1.

### 3.3. Discrete Correlation Function

We use a discrete correlation function (DCF) analysis introduced by Edelson & Krolik (1988) and later modified
Table 2. Flux and hardness ratio of HBLs

| Source     | Obs ID     | $\mu$ (counts/s) | Mean HR | $n$ | $\chi^2$ | $\chi^2_{0.99,n}$ |
|------------|------------|------------------|---------|-----|----------|-------------------|
|            |            | Soft 0.3–2 keV   | Hard 2–10 keV | Total 0.3–10 keV |
| 1ES 0229+200 | 0604210201 | 03.67 ± 0.22     | 01.22 ± 0.13 | 04.88 ± 0.26 | −0.50 ± 0.07 | 173 | 71.72 | 219.20 |
|            | 0604210301 | 03.67 ± 0.22     | 01.23 ± 0.13 | 04.88 ± 0.26 | −0.50 ± 0.07 | 212 | 100.57 | 262.80 |
| 1ES 0414+009 | 0094383101 | 10.70 ± 0.42     | 01.45 ± 0.16 | 12.13 ± 0.45 | −0.76 ± 0.06 | 104 | 18.50 | 140.50 |
|            | 0161160101 | 05.42 ± 0.17     | 00.54 ± 0.06 | 05.95 ± 0.19 | −0.82 ± 0.05 | 238 | 33.58 | 291.70 |
| PKS 0548−322 | 0142270101 | 14.27 ± 0.27     | 03.03 ± 0.13 | 17.20 ± 0.30 | −0.65 ± 0.03 | 200 | 50.18 | 259.50 |
|            | 0205920501 | 23.11 ± 0.52     | 04.79 ± 0.24 | 27.86 ± 0.57 | −0.66 ± 0.03 | 238 | 60.73 | 291.70 |
| 1ES 1101−232 | 0205920601 | 33.09 ± 0.63     | 06.06 ± 0.27 | 39.09 ± 0.68 | −0.69 ± 0.03 | 172 | 47.30 | 218.10 |
| 1H 1219+301  | 0111840101 | 42.90 ± 0.59     | 04.54 ± 0.20 | 47.44 ± 0.63 | −0.81 ± 0.02 | 141 | 32.04 | 183.00 |
| H 1426+428   | 0111850201 | 15.34 ± 0.29     | 03.79 ± 0.14 | 19.09 ± 0.32 | −0.60 ± 0.02 | 175 | 59.08 | 221.40 |
|            | 0165770101 | 19.67 ± 0.33     | 03.19 ± 0.13 | 22.82 ± 0.35 | −0.72 ± 0.02 | 186 | 41.30 | 233.80 |
|            | 0165770201 | 19.55 ± 0.32     | 03.20 ± 0.13 | 22.71 ± 0.35 | −0.72 ± 0.02 | 200 | 37.99 | 249.40 |
|            | 0212090201 | 24.57 ± 0.45     | 03.92 ± 0.18 | 28.44 ± 0.48 | −0.73 ± 0.03 | 143 | 25.31 | 185.30 |
|            | 0310190101 | 35.29 ± 0.53     | 06.91 ± 0.24 | 42.12 ± 0.59 | −0.67 ± 0.02 | 167 | 44.71 | 212.40 |
|            | 0310190201 | 28.04 ± 0.48     | 04.71 ± 0.20 | 32.69 ± 0.51 | −0.71 ± 0.02 | 200 | 35.69 | 249.40 |
|            | 0310190501 | 28.13 ± 0.48     | 04.02 ± 0.18 | 32.15 ± 0.51 | −0.75 ± 0.03 | 175 | 32.81 | 221.40 |
| Mrk 501     | 0652570101 | 27.25 ± 0.48     | 02.55 ± 0.15 | 29.77 ± 0.50 | −0.83 ± 0.03 | 197 | 22.79 | 246.10 |
|            | 0652570201 | 27.61 ± 0.47     | 02.47 ± 0.14 | 30.06 ± 0.49 | −0.84 ± 0.03 | 222 | 26.05 | 273.90 |
|            | 0652570301 | 27.02 ± 0.46     | 04.53 ± 0.19 | 31.50 ± 0.50 | −0.71 ± 0.03 | 202 | 39.04 | 251.70 |
|            | 0652570401 | 36.57 ± 0.54     | 06.10 ± 0.23 | 42.60 ± 0.59 | −0.71 ± 0.02 | 199 | 34.50 | 248.30 |
| 1ES 1959+650 | 0850980101 | 172.14 ± 1.62    | 37.00 ± 0.76 | 209.14 ± 1.78 | −0.65 ± 0.01 | 189 | 67.15 | 237.10 |
|            | 0870210101 | 123.55 ± 1.31    | 32.60 ± 0.68 | 156.15 ± 1.46 | −0.58 ± 0.01 | 156 | 51.85 | 200.00 |
| PKS 2005−489 | 0205920401 | 04.08 ± 0.23     | 00.21 ± 0.08 | 04.29 ± 0.25 | −0.90 ± 0.10 | 116 | 14.12 | 154.3 |
|            | 0304080301 | 23.80 ± 0.53     | 03.05 ± 0.20 | 26.85 ± 0.56 | −0.77 ± 0.03 | 144 | 18.82 | 186.40 |
|            | 0304080401 | 23.03 ± 0.52     | 02.87 ± 0.19 | 25.90 ± 0.55 | −0.78 ± 0.04 | 246 | 41.80 | 299.40 |
| 1ES 2344+514 | 0870400101 | 06.15 ± 0.22     | 01.53 ± 0.11 | 07.68 ± 0.25 | −0.60 ± 0.05 | 134 | 66.37 | 173.90 |

Note—$\mu$ is mean count rate. HR is hardness ratio. $n$ is the number of degrees of freedom. $\chi^2_{0.99,n}$ is the $\chi^2$ at 99 per cent confidence level for $n$ degrees of freedom.

by Hufnagel & Bregman (1992) to search for the cross-correlation and possible time lags between LCs in soft (0.3–2 keV) and hard (2–10 keV) energy bands. First we calculate the set of unbinned $UDCF_{ij}$ discrete correlations between soft and hard energy bands using

$$UDCF_{ij} = \frac{(a_i - \bar{a})(b_j - \bar{b})}{\sqrt{\sigma_a^2 \sigma_b^2}}.$$  (8)

Here $a_i$ and $b_j$ are soft and hard data points, $\bar{a}$, $\bar{b}$, $\sigma_a$ and $\sigma_b$ are means and standard deviations of the soft and hard data sets respectively. There exist a pairwise lag $\Delta t_{ij} = t_j - t_i$ corresponding to each of these $UDCF_{ij}$ values. After binning the correlation function, we calculate the DCF for a time lag $\tau$ defined by $\tau - \frac{\Delta t_{ij}}{2} \leq \Delta t_{ij} < \tau + \frac{\Delta t_{ij}}{2}$, by averaging the $UDCF_{ij}$ values as,
Table 3. X-ray variability parameters for HBLs

| Source | Obs ID     | $F_{\text{var}}$ | $|\tau|$(ks) | $|\tau|_{\text{corr}}$(ks) |
|--------|------------|------------------|--------------|-------------------------|
|        |            | Soft 2004-009    |              |                         |
| 1ES 0229+200 | 0604210201 | $-0.2 \pm 0.0$  | $-0.2 \pm 0.0$ | $-0.2 \pm 0.0$ |
| 0604210301 | $1.08 \pm 0.2$ | $0.61 \pm 0.2$ | $0.61 \pm 0.2$ | $0.61 \pm 0.2$ |
| 1ES 0414+009 | 0094383101 | $0.93 \pm 0.1$  | $1.69 \pm 0.1$ | $1.69 \pm 0.1$ |
| 0161160101 | $0.64 \pm 0.1$  | $2.06 \pm 0.1$ | $2.06 \pm 0.1$ | $2.06 \pm 0.1$ |
| PKS 0548–322 | 0142270101 | $0.76 \pm 0.1$  | $2.24 \pm 0.1$ | $2.24 \pm 0.1$ |
| 0205920501 | $1.30 \pm 0.1$  | $6.19 \pm 0.1$ | $6.19 \pm 0.1$ | $6.19 \pm 0.1$ |
| 1H 1219+301 | 0111840101 | $1.87 \pm 0.1$  | $11.00 \pm 0.1$ | $11.00 \pm 0.1$ |
| H 1426+428 | 0118502001 | $1.65 \pm 0.1$  | $11.00 \pm 0.1$ | $11.00 \pm 0.1$ |
| PKS 0048+058 | 0139050101 | $0.82 \pm 0.1$  | $4.32 \pm 0.1$ | $4.32 \pm 0.1$ |
| 0301905051 | $0.41 \pm 0.1$  | $1.05 \pm 0.1$ | $1.05 \pm 0.1$ | $1.05 \pm 0.1$ |
| Mrk 501 | 0652701001 | $0.22 \pm 0.1$  | $0.34 \pm 0.1$ | $0.34 \pm 0.1$ |
| 0652702001 | $1.65 \pm 0.1$  | $1.50 \pm 0.1$ | $1.50 \pm 0.1$ | $1.50 \pm 0.1$ |
| 1ES 1959+650 | 0508900101 | $1.30 \pm 0.1$  | $16.25 \pm 0.1$ | $16.25 \pm 0.1$ |
| 0807010101 | $1.72 \pm 0.1$  | $19.11 \pm 0.1$ | $19.11 \pm 0.1$ | $19.11 \pm 0.1$ |
| PKS 0048+058 | 0205920401 | $0.28 \pm 0.1$  | $0.37 \pm 0.1$ | $0.37 \pm 0.1$ |
| 0304080301 | $3.45 \pm 0.1$  | $0.86 \pm 0.1$ | $0.86 \pm 0.1$ | $0.86 \pm 0.1$ |

Note: Sig denotes significance and is calculated by $\text{Sig} = F_{\text{var}}/\text{err}(F_{\text{var}})$. Var represents the variability and can take values V for variable LC and NV for non-variable LC. $|\tau|$ and $|\tau|_{\text{corr}}$ are the variability timescale and red shift corrected variability timescale, respectively. Dash represents fractional variance could not be calculated as the sample variance was less than mean square error.
\[
DCF(\tau) = \frac{\sum UDCF_{ij}}{M} \quad (9)
\]
where \(M\) is the number of \(UDCF_{ij}\) pairs over which \(DCF\) is averaged. The standard error \(\sigma_{DCF}(\tau)\) associated with each bin is (Edelson & Krolik 1988)
\[
\sigma_{DCF}(\tau) = \sqrt{\frac{\sum (UDCF_{ij} - DCF(\tau))^2}{M - 1}}. \quad (10)
\]

A DCF peak value > 0 implies soft and hard data sets are correlated at that lag, while a DCF peak < 0 implies they are anti-correlated. We can use the autocorrelation function (ACF, where \(a = b\)) to perform a crude search for periods in these astronomical time series. If an observational time series contains periodic signals the ACF distribution would also show an oscillation at that period.

3.4. Hardness Ratio

We can investigate the X-ray spectral behavior in the coarse fashion prescribed by the relatively low counts in each temporal bin by computing the hardness ratio (HR) in ten of these blazars. Looking at any changes in HR for a given source lets us search for spectral variability; it is simply given by

\[
HR = \frac{H - S}{H + S}. \quad (11)
\]

Here \(H\) and \(S\) denote the hard (2–10 keV) and soft (0.3–2 keV) net count rates. The error associated with a HR measurement, \(\sigma_{HR}\), is

\[
\sigma_{HR} = \frac{2 \sqrt{S^2 \sigma^2_H + H^2 \sigma^2_S}}{(H + S)^2}, \quad (12)
\]
where $\sigma_H$ and $\sigma_S$ are the uncertainty in hard and soft band, respectively. We perform a standard $\chi^2$ test to investigate possible temporal variations in $HR$:

$$\chi^2 = \sum_{j=1}^{n} \frac{(x_j - \bar{x})^2}{\sigma_j^2},$$  \hspace{1cm} (13)

where $x_j$ and $\sigma_j$ denote the HR value for the $j^{th}$ data point and its associated error, while $\bar{x}$ is mean value of all HR values.

### 3.5. Power Spectral Density

The power spectral density (PSD) provides the amount of variability power as a function of temporal frequency and is an useful tool to search for presence of possible periodicities and quasi-periodic oscillations (QPOs) in a LC. For AGNs, the PSD usually shows red noise behavior at lower frequency that changes to white noise behavior at higher frequencies where measurement errors prevail. The standard procedure for evaluating a PSD is by calculating the periodogram (Vaughan et al. 2003). While computing periodogram function using scipy module, we normalize it in units of $(\text{rms/mean})^2$.

We employ Bayesian statistics and maximum likelihood estimation in fitting the periodogram, as discussed in Vaughan (2010). The best-fitting parameter $\theta$ for a particular parametric model $P(\nu, \theta)$ is assessed by maximizing the likelihood function, which is equivalent to minimizing the following fit statistic,

$$S = 2 \sum_{j=1}^{N/2} \frac{I_j}{P_j} \ln P_j,$$  \hspace{1cm} (14)

Here $S$ is twice the minus log-likelihood, $P_j$ and $I_j$ are observed model spectral density and periodogram at Fourier frequency $f_j$, respectively. A significant QPO may be claimed if a peak rises at least $3\sigma$ (i.e. 99.73%) above the red noise fit of the PSD. We adopt a simple power law plus a constant form to fit the PSDs of these X-ray LCs (González-Martín & Vaughan 2012; Mohan & Mangalam 2015),

$$P(f) = N f^{-\alpha} + C$$  \hspace{1cm} (15)

The model uses three parameters: $N$, normalization constant for the power law fitting; $\alpha$, the spectral index for power law fitting; $C$, an additive constant to take care of the Poisson noise.

### 4. RESULTS

We now discuss the results obtained on applying the analysis techniques discussed in section 3 to the XMM-Newton data given in Table 1.

Figure 6. PSD plot for XMM-Newton observation of 1H 1219+301 with observation ID 0111840101 in the soft (top), hard (middle) and total (bottom) X-ray band. The obtained spectral index are also shown.

#### 4.1. Intraday X-ray flux variability

We produced X-ray LCs for all 10 HBLs spanning over 25 observations observed by EPIC-PN instrument of XMM-Newton in the soft, hard, and total energy bands. Examples of a variable (top panel, 1H 1219+301) and a non-variable (bottom panel, Mrk 501) total LC are shown in Figure 1. Corresponding LCs in the soft (left panel) and hard (right panel) energy bands are plotted in Figure 2. Similar LCs for all other observations IDs
are given in Figure A1 and Figure A2.

On visual inspection of these plots, one observation of Mrk 501 and one of 1H 1219+301 appeared to exhibit variability on IDV timescales in the total energy band, while 1ES 1959+650 and H 1426+428 showed variability in multiple observations. To investigate the variability of all of these blazars in IDV time scales and to quantify their variability amplitudes, we used the excess variance method discussed in subsection 3.1 and the obtained results are reported in Table 3. Following Dhiman et al. (2021), we consider a LC to be variable only when its sample variance is greater than the mean square error and $F_{\text{var}} > 3 \times (F_{\text{var}})_{\text{err}}$. We calculated $F_{\text{var}}$ and associated error $(F_{\text{var}})_{\text{err}}$ in all three energy bands for 25 observations.

Three sources (1ES 0229+200, 1ES 0414+009 and PKS 2005-489) did not show variability in any energy bands in any of the observations. All observations of 1H 1219+301, 1ES 2344+514 and 1ES 1959+650 exhibited variability in all energy bands. Among the seven observations of H 1426+428, the source exhibited variability in all energy bands only in two observations (0111840101 and 0310190101), while in the rest of the observations the source is variable in one or two bands (see Table 2). PKS 0548-322 did not display any variability in one observation (0205920501), while it showed variability in the total band during the other observation (0142270101). Mrk 501 did not show any variability in observation 0652570101, while the remaining three observations displayed variability in one or more bands. The single observation of 1ES 1101-232 revealed variability in both soft and total bands. Moreover, one observation each of Mrk 501 (Obs ID 0652570101) and H 1426+428 (Obs ID 0310190101) did not show variability in the hard band alone. However, in these cases the ratio of $F_{\text{var}}$ to $(F_{\text{var}})_{\text{err}}$ barely exceeds 3. In summary, among the 25 observations considered in this work, 15 of them showed intraday variability in at least one band. These $F_{\text{var}}$ results, along with the corresponding variability time scales in the soft, hard and total energy bands are

| Source   | Obs ID          | Soft (0.3–2 keV) | Hard (2–10 keV) | Total (0.3–10 keV) |
|----------|-----------------|------------------|-----------------|-------------------|
|          |                 | $\log_{10}N$     | $\alpha$        | $\log_{10}N$     | $\alpha$         |
| 1ES 0229+200 | 0604210201     | NV               | NV              | NV                |
| 1ES 0414+009 | 0094383101     | NV               | NV              | NV                |
| PKS 0548-322 | 0142270101     | NV               | NV              | NV                |
| 1ES 1101–232 | 0205920401     | –                | –               | –                 |
| 1H 1219+301 | 0111840101     | $-11.77 \pm 0.64$| $-9.26 \pm 0.45$| $-11.79 \pm 0.75$|
| H 1426+428 | 0111850201     | $-11.74 \pm 0.96$| $-9.79 \pm 0.83$| $-11.72 \pm 1.18$|
| Mrk 501   | 0652570101     | NV               | NV              | NV                |
| PKS 2005-489 | 0205920401     | NV               | NV              | NV                |
| 1ES 1959+650 | 0850980101     | $-8.16 \pm 0.31$| $-7.04 \pm 0.76$| $-7.96 \pm 0.55$  |
| PKS 0548-322 | 0304080301     | NV               | NV              | NV                |
| 1ES 2344+514 | 0870400101     | –                | –               | –                 |

Note–N and $\alpha$ denote normalisation and spectral index, respectively.

NV denotes observation is non-variable.

– indicates variations were too small to compute a power spectral density.
reported in Table 2. For further analysis, we consider only these 15 observations unless otherwise specified.

We also performed auto-correlation function analysis to see if there was any hint of periodicities in the 15 variable LCs. An example of an ACF plot is shown in Figure 4. Similar ACF plots for other variable LCs are given in Figure A4. Most of the ACF plots are noisy and those which are not noisy do not show any peak other than at zero lag, so we see no evidence for any periods.

4.2. Intraday cross-correlated variability

We have followed discrete correlation function (DCF) analysis technique discussed in subsection 3.3 to determine cross correlations and time lags between hard and soft X-ray bands. The DCF plot for 1H 1219+301 is shown as an example in Figure 3. Similar DCF plots for 15 variable LCs are given in Figure A3. We note that the single observation of H 1219+301 and both observations of 1ES 1959+650 showed a significant DCF values (> 0.5) at non-zero time lags between the hard and soft bands. In these three cases we fit the DCF with a Gaussian function of form:

$$DCF(\tau) = a \exp\left(-\frac{(\tau - m)^2}{2\sigma^2}\right),$$

where $a$ is the DCF peak value, $m$ is the time lag at which DCF peaks and $\sigma$ is the width of the Gaussian function. Through these fits we found positive time lags of 0.70 ks and 0.57 ks, respectively for 1H 1219+301 (0111840101) and 1ES 1959+650 (0870210101), which indicate soft energy emission precedes hard energy emission for this observation.

Intraday spectral variability

We investigated X-ray spectral variations on IDV timescales through measurements of the hardness ratio (HR). The mean HR for each LC, numbers of degree of freedom, $\chi^2$ value, and $\chi^2$ at 99 per cent significance level are given in Table 2. An example of HR plot for the variable (top panel) and non variable (bottom panel) LCs are given in Figure 5. HR plots for the rest of the observations can be found in Figure A5. We included all 25 observations in this analysis. On visual inspection of the HR plots, we did not find any spectral variations. To investigate the spectral variability quantitatively, we performed $\chi^2$ tests as discussed in subsection 3.4. If $\chi^2 > \chi^2_{99,n}$ (the 99 per cent confidence level for the number of degrees of freedom, $n$), the source is considered to have spectral variations. We did not find significant variations in the HR for any of the observations according to the $\chi^2$ test. These results are not surprising in that we never observed large variability amplitude in the fluxes themselves.

4.4. Intraday power spectral density analysis

We performed PSD analyses on all 15 variable LCs to characterize the type of noise present in the variations and to search for any QPOs present during those spans. Studies done on a large number of X-ray light-curves has confirmed the fact that PSDs are red noise dominated, following a power-law $P(\nu) \approx \nu^{-\alpha}$ where $\nu$ is the temporal frequency and $\alpha$ is the spectral index, until they flatten into white noise. González-Martín & Vaughan (2012) reported that X-ray variable LCs of a large sample of AGN have $\alpha \approx 2$. Following Vaughan (2010) and Pavana Gowtami et al. (2022), we fit power-law model to the variable X-ray LCs of the 15 observations as discussed in subsection 3.5. The slope $\alpha$ and logarithm of normalization constant $\log_{10} N$ are tabulated in Table 4. PSD plots for soft (0.3–2 keV), hard (2–10 keV) total (0.3–10 keV) variable LCs of 1H 1219+301 with observation ID 0111840101 are given in Figure 6. Similar PSD plots for variable LCs in different energy bands are given in Figure A6, Figure A7, and Figure A8.

5. DISCUSSION

The analysis of flux variations on diverse timescales across all EM bands will aid us in understanding emission mechanisms in blazars and other AGNs. Study of rapid flux variations in blazars can be used as a tool to estimate key features of emitting regions in jets such as their sizes, locations, and sometimes structures (e.g. Ciprini et al. 2003). Two fundamental classes of models can explain intrinsic AGN emission and flux variability: (a) relativistic-jet-based models (e.g. Marscher & Gear 1985; Gopal-Krishna & Wiita 1992; Marscher 2014; Calafut & Wiita 2015); (b) accretion-disk-based models (e.g Mangalam & Wiita 1993; Chakrabarti & Wiita 1993). In the case of blazars, in particular BL Lac
objects, the relativistic jet emission dominates and any contribution from the accretion disk can be noticed only when the BL Lac is observed in a low flux state. IDV and STV seen in radio-quiet AGNs and blazars, particularly FSRQs in low flux states can be explained by accretion-disk-based models. For them brightness fluctuations on these timescales can be due to hot spots on or above the disk or arise from larger scale disk related instabilities that might be caused by a tilted disk or a dynamo (e.g. Chakrabarti & Wiita 1993; Mangalam & Wiita 1993; Henisey et al. 2012; Sądowski & Narayan 2016).

In this sample, 1H 1219+301 has the minimum weighted variability timescale $\tau_{\text{var},m} = 3.65 \pm 1.21$ ks for the observation ID 0111840101. By utilizing the simplest causality argument, the $\tau_{\text{var},m}$ can be used to estimate an upper limit for the size of emitting region, $R$, as

$$R \leq \frac{\delta}{1 + z} \frac{c \tau_{\text{var},m}}{1 + z}.$$  

Here $\delta$ is the Doppler factor; unfortunately, for 1H 1219+301 this value, estimated using leptonic models in different EM bands and in different flux states, covers a wide range between 20 and 80 (Sato et al. 2008; Rüger et al. 2010; Cerruti et al. 2015; Singh et al. 2019; Sahakyan 2020). We now assume that the varying X-ray emission originates from a region in the relativistic jet. Taking $\tau_{\text{var},m} = 3.65$ ks, along with the complete range of Doppler factors ($\delta = 20 – 80$), and $z = 0.1836$ (see Table 1) and making use of equation (17), we find that the upper limit to the size of the emission region lies in the range $(1.9 - 7.4) \times 10^{15}$ cm.

We can derive some other important parameters for these HBLs, by continuing to consider the scenario in which the emission arises from relativistic jets. As already discussed, hard X-ray emission from HBLs is understood to be generated by synchrotron emission from relativistic electrons in the jet (e.g Pandey et al. 2018). A diffusive shock acceleration mechanism (e.g. Blandford & Eichler 1987) is very likely to be responsible for electron acceleration within jets and in that case the acceleration timescale for electron of energy $E = \gamma m_e c^2$ in the observer’s frame is given in Zhang et al. (2002) as

$$t_{\text{acc}}(\gamma) \simeq 3.79 \times 10^{-7} \frac{1 + z}{\delta} \frac{\xi \gamma}{B} \text{ s}.$$  

Here $\delta$ is the Doppler factor, $B$ is the magnetic field in Gauss, $\gamma$ is the electron Lorentz factor, and $\xi$ is the electron acceleration parameter which comes from the relation between mean free path and electron Larmor radius:

$$\lambda(\gamma) = \gamma m_e c^2 \xi / (\epsilon B) \quad \text{(Kusunose et al. 2000).}$$

The synchrotron cooling timescale for an individual electron in observer’s frame is given in Rybicki & Lightman (1985) as,

$$t_{\text{cool}}(\gamma) \simeq 7.74 \times 10^8 \frac{1 + z}{\delta} \frac{1}{B^2 \gamma} \text{ s}. \quad (19)$$

For a given $B$ and $\gamma$, the characteristic X-ray frequency at which synchrotron emission peaks, the critical synchrotron emission frequency, is (Paliya et al. 2015; Dhimian et al. 2021)

$$\nu \simeq 4.2 \times 10^6 \frac{\delta}{1 + z} B \gamma^2 \text{ Hz} \simeq 10^{18} \nu_{18} \text{ Hz}, \quad (20)$$

where $0.73 \leq \nu_{18} \leq 2.42$ for X-rays in XMM-Newton’s total energy range of $0.3 – 10$ keV. Imposing the condition that the synchrotron cooling timescale of electrons radiating in the XMM-Newton range has to be no greater than the observed minimum variability timescale, we have following inequality (Paliya et al. 2015)

$$t_{\text{cool}}(\gamma) \leq \tau_{\text{var},m}. \quad (21)$$

We combine Eqns. (19) and (20) to come up with an expression for $t_{\text{cool}}(\gamma)$ without an explicit dependence on $\gamma$ and substitute it in above inequality Eqn (21) along with $\tau_{\text{var},m} = 3.65$ ks, we arrive at a constraint on the magnetic field for 1H 1219+301 as,

$$B \geq 0.61 \delta^{-1/3} \nu_{18}^{-1/3} \text{ G}. \quad (22)$$

Using the complete range of Doppler factors (ie $\delta \sim 20 – 80$) we find this lower limit for $B$ lies in the rather narrow range of $(0.14 – 0.22) \nu_{18}^{-1/3}$ G. Previous estimations of the magnetic field for 1H 1219+301 at different flux state and different epochs vary between $0.01 – 0.22$ G (e.g. Singh et al. 2019; Sahakyan 2020). As $\nu_{18}$ can have any value between 0.73 and 2.73, our magnetic field estimate is consistent with previous values. Using Eqns. (20) and (22), we now can set a constraint on the electron Lorentz factor for 1H 1219+301 as well,

$$\gamma \leq 6.8 \times 10^5 \delta^{-1/3} \nu_{18}^{2/3}. \quad (23)$$

Again taking the complete range of Doppler factor, we find upper limits to $\gamma$ in the range $1.6 \times 10^5 \nu_{18}^{2/3} – 2.5 \times 10^5 \nu_{18}^{2/3}$. This is consistent with a previous estimate of $\gamma \sim 5 \times 10^5$ (Rüger et al. 2010), if we take into account uncertainty associated with $\tau_{\text{var},m}$ as well as the allowed range for $\nu_{18}$.

The maximum energy of $\gamma$-ray photons generated by relativistic electrons through Compton scattering in
Table 5. Model parameters for HBL blazars

| Source [1] | $\tau_{var,m}$ [2] (ks) | $x$ [3] | $\delta$ [4] | $R$ [5] | $B$ [6] | $\gamma$ [7] | $E_{T,max}$ [8] /$\nu_{18}^{1/3}$/G $\nu_{18}^{2/3}$/TeV $\nu_{2/3}$/TeV |
|------------|-----------------|---------|------|--------|-----|--------|-----------------|
| PKS 0548-322 | 4.75 | 0.0690 | 10 − 20 [a] | < 1.3 − 2.7 | > 0.18 − 0.23 | < 2.7 − 3.3 | $\approx 1.6 − 2.6$ |
| 1ES 1101−232 | 1.23 | 0.1860 | 10 − 60 [b] | < 0.3 − 1.9 | > 0.32 − 0.59 | < 1.2 − 2.2 | $\approx 0.9 − 3.1$ |
| 1H 1219+301 | 3.65 | 0.1836 | 20 − 80 [c] | < 1.9 − 7.4 | > 0.14 − 0.22 | < 1.6 − 2.5 | $\approx 2.2 − 5.5$ |
| H 1426+428 | 2.71 | 0.1293 | 11 − 27,3 [d] | < 0.8 − 2.0 | > 0.24 − 0.33 | < 2.0 − 2.7 | $\approx 1.4 − 2.5$ |
| Mrk 501 | 3.38 | 0.0330 | 8.3 − 50 [e] | < 0.8 − 4.9 | > 0.17 − 0.30 | < 1.7 − 3.1 | $\approx 1.3 − 4.2$ |
| 1ES 1959+650 | 4.51 | 0.0470 | 15 − 60 [f] | < 1.9 − 7.8 | > 0.13 − 0.21 | < 1.8 − 2.8 | $\approx 2.1 − 5.3$ |
| 1ES 2344+514 | 1.51 | 0.0440 | 8.4 − 23 [g] | < 0.4 − 1.0 | > 0.40 − 0.50 | < 1.6 − 2.4 | $\approx 1.0 − 1.8$ |

Note—[1] Name of the source; [2] Minimum variability timescale; [3] Red-shift; [4] Range of Doppler factor values; [5] Characteristic size of emitting region; [6] Magnetic field; [7] Electron Lorentz factor; [8] Maximum electron energy in Thomson region.

[a] Sato et al. (2008); Rüger et al. (2010) [b] Zheng & Kang (2013); Abdo et al. (2010) [c] Sato et al. (2008); Salakyan (2020) [d] Wolter et al. (2008); Piner et al. (2008) [e] Kino et al. (2002); Albert et al. (2007a); Pandey et al. (2017) [f] Patel et al. (2018); MAGIC Collaboration et al. (2020) [g] Albert et al. (2007b); Rügamer et al. (2011)

Using Eqn. (23), $z = 0.1836$, and the same range of $\delta$ values, we see that $2.2 \times 10^{23}$ TeV $\leq E_{T,max} \leq 5.5 \times 10^{23}$ TeV.

Similarly, we estimate all these parameters for the remaining 6 variable HBLs and report them in Table 5.

6. CONCLUSIONS

We studied 25 LCs of ten TeV HBLs which were observed by XMM-Newton during its complete operational period. We searched for IDV and variability timescales, lags between soft and hard energy bands, spectral variations through analysis of hardness ratio changes, and also performed PSD analyses to characterize the type of noise present and to search for the presence of possible QPOs.

We summarize our conclusions as follows:

1. The fractional variability amplitude analysis clearly shows 7 of 10 HBLs exhibit IDV for at least one observation in total energy band (0.3−10 keV). 1ES 1101−232, 1H 1219+301 and 1ES 2344+514 showed IDV in their single observation. 1ES 1959+650 displayed IDV in both of its observations, while PKS 0548−322 displayed IDV only in one of two observations. Two of the four observations of Mrk 501 and six of the seven observations of H 1426+428 exhibited IDV. However, there were no major variations; the highest variability amplitude was just below 6 per cent.

2. In general, $F_{var}$ is lower in the soft band (0.3−2 keV) than in the hard band (2−10 keV) with the exception of one observation, where they are comparable (i.e., in the case of H 1426+428 and Obs ID 0212009201). We estimated variability timescales and determined a minimum variability timescale ($\tau_{var,m}$) for each of the seven HBLs. Then, we used $\tau_{var,m}$ to estimate various parameters such as the size of the emission region, the magnetic field in that region and the electron Lorentz factor for the ultra-relativistic electrons emitting X-rays in each of these HBLs.

3. Most of the ACF plots were noisy and we did not find any indication of a variability timescale from this approach.

4. DCF plots for most of these TeV HBLs are almost flat, which indicates that there could be no correlation between soft and hard energy bands. This however, is more likely due to very low fluxes in the hard band, which makes it difficult to detect correlations. However, for both observations of 1ES 1959+650 and the single observation of 1H 1219+301, DCF peaks at non-zero lags indicate the possibility that much of the soft X-ray might originate from synchrotron emission, while the hard X-rays may be dominated by a SSC origin.

5. We performed hardness ratio analysis to attempt to study X-ray spectral variations of these 10 blazars, but found no significant variations.

6. PSD analyses in the soft, hard, and total X-ray energy bands were performed for the 15 variable
LCs. We found that PSDs are dominated by red noise and no evidence for a possible QPOs was found in any of the PSD plots. PSD was fitted using power low model at lower frequencies and their slopes range from $1.11$ to $2.93$.

ACKNOWLEDGEMENTS
We thank the anonymous referee for the constructive comments and suggestions that improved this manuscript. This research is based on observations obtained with XMM–Newton, an ESA science mission with instruments and contributions directly funded by ESA member states and NASA.

Software: HEAsoft (NASA High Energy Astrophysics Science Archive Research Center (HEASARC) 2014), SAS (Gabriel et al. 2004)

REFERENCES
Abdo, A. A., Ackermann, M., Agudo, I., et al. 2010, ApJ, 716, 30, doi: 10.1088/0004-637X/716/1/30
Aggrawal, V., Pandey, A., Gupta, A. C., et al. 2018, MNRAS, 480, 4873, doi: 10.1093/mnras/sty2173
Albert, J., Aliu, E., Anderhub, H., et al. 2007a, ApJ, 669, 862, doi: 10.1086/521382
—. 2007b, ApJ, 662, 892, doi: 10.1086/518431
Bhatta, G., Mohorian, M., & Bilinsky, I. 2018, A&A, 619, A93, doi: 10.1051/0004-6361/201833628
Blandford, R., & Eichler, D. 1987, PhR, 154, 1, doi: 10.1016/0370-1573(87)90134-7
Blandford, R. D., & Levinson, A. 1995, ApJ, 441, 79, doi: 10.1086/175338
Blandford, R. D., & Rees, M. J. 1978, PhyS, 17, 265, doi: 10.1088/0004-637X/718/1/2703
Bloom, S. D., & Marscher, A. P. 1996, ApJ, 461, 657, doi: 10.1086/177092
Burbidge, G. R., Jones, T. W., & O’Dell, S. L. 1974, ApJ, 193, 43, doi: 10.1086/153125
Calafut, V., & Wiita, P. J. 2015, Journal of Astrophysics and Astronomy, 36, 255, doi: 10.1007/s12036-015-9324-2
Cerruti, M., Zech, A., Boisson, C., & Inoue, S. 2015, MNRAS, 448, 910, doi: 10.1093/mnras/stu2691
Chakrabarti, S. K., & Wiita, P. J. 1993, ApJ, 411, 602, doi: 10.1086/172862
Ciprini, S., Testi, G., Raiteri, C. M., et al. 2003, A&A, 400, 487, doi: 10.1051/0004-6361:20030045
Dermer, C. D., & Schlickeiser, R. 1994, ApJS, 90, 945, doi: 10.1086/191929
Dhiman, V., Gupta, A. C., Gaur, H., & Wiita, P. J. 2021, MNRAS, 506, 1198, doi: 10.1093/mnras/stab1743
Edelson, R., Turner, T. J., Pounds, K., et al. 2002, ApJ, 568, 610, doi: 10.1086/323779
Edelson, R. A., & Krolik, J. H. 1988, ApJ, 333, 646, doi: 10.1086/166773
Foschini, L. 2020, Universe, 6, 136, doi: 10.3390/universe6090136
Fossati, G., Buckley, J. H., Bond, I. H., et al. 2008, ApJ, 677, 906, doi: 10.1086/527311
Gabriel, C., Denby, M., Kyte, D. J., et al. 2004, in Astronomical Society of the Pacific Conference Series, Vol. 314, Astronomical Data Analysis Software and Systems (ADASS) XIII, ed. F. Ochsenbein, M. G. Allen, & D. Egret, 759
Gaur, H., Gupta, A. C., Lachowicz, P., & Wiita, P. J. 2010, ApJ, 718, 279, doi: 10.1088/0004-637X/718/1/279
Ghisellini, G., Villata, M., Raiteri, C. M., et al. 1997, A&A, 327, 61. https://arxiv.org/abs/astro-ph/9706254
González-Martín, O., & Vaughan, S. 2012, A&A, 544, A80, doi: 10.1051/0004-6361/201219008
Gopal-Krishna, & Wiita, P. J. 1992, A&A, 259, 109
Goyal, A., Gopal-Krishna, Anupama, G. C., et al. 2009, MNRAS, 399, 1622, doi: 10.1111/j.1365-2966.2009.15385.x
Gupta, A. C., Banerjee, D. P. K., Ashok, N. M., & Joshi, U. C. 2004, A&A, 422, 505, doi: 10.1051/0004-6361:20040306
Gupta, A. C., Kalita, N., Gaur, H., & Duorah, K. 2016, MNRAS, 462, 1508, doi: 10.1093/mnras/stw1667
Hagen-Thorn, V. A., Larionov, V. M., & Jorstad, S. G., et al. 2008, ApJ, 672, 40, doi: 10.1086/523841
Henisey, K. B., Blaes, O. M., & Fragile, P. C. 2012, ApJ, 761, 18, doi: 10.1088/0004-637X/761/1/18
Hufnagel, B. R., & Bregman, J. N. 1992, ApJ, 386, 473, doi: 10.1086/171033
Kalita, N., Gupta, A. C., Wiita, P. J., Bhagwan, J., & Kusunose, M. 2015, MNRAS, 451, 1356, doi: 10.1093/mnras/stv1182
Kino, M., Takahara, F., & Kusunose, M. 2002, ApJ, 564, 97, doi: 10.1086/323363
APPENDIX

A. APPENDIX SECTION
Figure A1. Light curves (LCs) of 25 XMM-Newton pointed observations of HBLs in total (0.3–10 keV) energy band. Source name and Observation ID are given in each plot.
Figure A1. Continued
Figure A1. Continued
Figure A2. LCs of 25 XMM-Newton pointed observations in the soft energy (0.3–2 keV; blue dots) and in the hard energy (2–10 keV; red dots). Source name and Observation ID are given above each plot.
Figure A2. Continued.
Figure A2. Continued.
Figure A3. Discrete Correlation Function (DCF) plots for variable light curves labeled with source names and Observation IDs.
Figure A3. Continued.
Figure A4. Auto Correlation Function (ACF) plots for variable light curves labeled with source names and Observation IDs.
Figure A4. Continued.
Figure A5. Hardness Ratio (HR) of 25 XMM-Newton pointed observations labeled with source name and Observation ID.
Figure A5. Continued.
X-ray intraday variability of HBLs

Figure A5. Continued.
Figure A6. Power Spectral Density (PSD) plots for soft energy band light curves. Also shown are fits to the red noise (black curve), the white noise level (dotted line) and 3\(\sigma\) level above the noise (red dotted curve). The source and observation ID as well as the PSD index are given in each plot.
Figure A7. PSD for the hard energy band. The labelling is same as that of Figure A6
Figure A8. PSD for the total energy band. The labelling is same as that of Figure A6.
Figure A8. Continued.