X-Ray Flux and Spectral Variability of Six TeV Blazars with NuSTAR

Ashwani Pandey1,2, Alok C. Gupta1,2, and Paul J. Wiita3

1 Aryabhata Research Institute of Observational Sciences (ARIES), Manora Peak, Nainital 263002, India; ashwanitapan@gmail.com
2 Department of Physics, DDU Gorakhpur University, Gorakhpur 273009, India; agupta30@gmail.com
3 Department of Physics, The College of New Jersey, 2000 Pennington Rd., Ewing, NJ 08628-0718, USA; wiiatap@tcnj.edu

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Abstract

We report the first results of timing and spectral studies of Nuclear Spectroscopic Telescope Array observations of six TeV-emitting high-frequency peaked blazars: 1ES 0347-121, 1ES 0414+009, RGB J0710+591, 1ES 1101-232, 1ES 1218+304, and H 2356-309. Two out of these six TeV blazars, 1ES 1101−232 and 1ES 1218+304, showed strong evidence of intraday variations in the 3–79 keV energy range during those observations. We also found a hint of an intraday variability timescale of 23.5 ks in the light curve of 1ES 1218+304 using an autocorrelation function analysis. We obtained a magnetic field \( B \approx 0.03 \) G, electron Lorentz factor \( \gamma \approx \frac{2.16 \times 10^6}{R} \), and emission region size \( R \approx 1.19 \times 10^{16} \) cm for 1ES 1218+304 using that variability timescale. The other blazars’ light curves do not show any variability timescales shorter than their observation lengths; however, we note that the data were both noisier and sparser for them. We also investigated the spectral shape of these TeV blazars and found that the spectrum of 1ES 0414+009 is well described by a single power law with a photon index \( \Gamma \approx 2.77 \). The spectra of the other five HBLs are somewhat better represented by log-parabola models with local photon indices (at 10 keV) \( \alpha \approx 1.23 \) – 2.67 and curvature parameters \( \beta \approx 0.27 \) – 0.43.

Key words: BL Lacertae objects: general – galaxies: active

1. Introduction

Blazars are the subclass of active galactic nuclei (AGNs) characterized by a relativistic jet that is aligned close (<10\(^5\)) to the observer’s line of sight (Urry & Padovani 1995). The Doppler-boosted non-thermal emission from the relativistic jets is highly variable at all observed timescales over essentially the entire electromagnetic spectrum. Variability seen over a timescale of less than a day is called intraday variability (IDV), or microvariability (Wagner & Witzel 1995), variations over a few days to months are often called short-term variability (STV), and fluctuations observed over several months to years, or even decades, are known as long-term variability (LTV; Gupta et al. 2004). The two classical subclasses of blazars are BL Lacertae objects (BL Lacs), which have no detectable, or very weak (EW < 5\(\alpha\)), optical emission lines (Marcha et al. 1996), and flat spectrum radio quasars (FSRQs), which have the usual strong quasar emission lines in their optical spectra. The two broad bumps seen in the broadband spectral energy distributions (SEDs) of blazars indicate two different emission mechanisms. The low-energy peak is well understood to be caused by the synchrotron emission from relativistic electrons in the jet. However, the origin of the high-energy peak is still under debate. In the leptonic model, the high-energy component is interpreted as the inverse Compton (IC) scattering of synchrotron photons themselves (synchrotron-self Compton, SSC; e.g., Bloom & Marscher 1996), or external photons (external Compton, EC; e.g., Blandford & Levinson 1995) by the same electrons responsible for the synchrotron emission. In the alternative hadronic models, processes such as proton and muon synchrotron emission are thought to be responsible for the high-energy bump (e.g., Böttcher 2007). Blazars are also classified through the value of the peak frequency of the synchrotron component. It typically lies in the infrared to optical region in the low-frequency peak blazars (LBL), while in the high-frequency peaked blazars (HBL) it is located at FUV to X-ray energies (Padovani & Giommi 1995). The high-energy components of blazar SEDs peak at GeV energies in LBLs and at TeV energies in HBLs, but some LBLs and the intermediate-peaked blazars (IBLs) have still been detected at TeV energies.

The X-ray emissions of TeV blazars are found to be highly variable at IDV timescales (e.g., Pandey et al. 2017 and references therein) as they correspond to the high-energy tail of the synchrotron component of their SEDs. Study of X-ray variability at IDV timescales is useful for understanding the underlying physical mechanisms and for constraining the properties of emitting regions. The nature of the X-ray spectra of TeV-emitting blazars has been examined for quite some time. Worral & Wilkes (1990) found that a single power law (PL) with spectral indices ∼1.0 provided acceptable fits to the X-ray spectra of 24 BL Lac objects observed with the Einstein Observatory. The X-ray spectra of a large sample of BL Lac objects in the BeppoSAX spectral survey of BL Lacs were well described by either a single PL or a broken PL (Beckmann et al. 2002). In more recent studies, the X-ray spectra of TeV blazars were found to be curved at high energies and were better fitted with a log-parabola (LP) model (e.g., Giommi et al. 2002; Donato et al. 2005; Tramacere et al. 2007b; Massaro et al. 2008). The LP model was first used by Landau et al. (1986) to better describe the synchrotron emission of BL Lac objects, but they did not provide any physical explanation of the model. Later, Massaro et al. (2004a, 2004b, 2006) described the X-ray spectra of TeV BL Lac objects Mrk 421 and Mrk 501 in terms of the curved LP model and also gave a possible interpretation of this model in terms of statistical particle acceleration by assuming that the probability of an increase in the energy of an emitting particle is a decreasing function of its energy. In a recent study with Swift/XRT, Wierzcholska & Wagner (2016) found that most of the X-ray spectra of TeV-emitting blazars are well described by the LP model.
The X-ray observatory, *Nuclear Spectroscopic Telescope Array (NuSTAR)*, launched in 2012, consists of two co-aligned hard X-ray telescopes that focus on two almost identical detector modules, Focal Plane Module A (FPMA) and Focal Plane Module B (FPMB; Harrison et al. 2013). Its high spectral resolution and low background have provided unprecedented sensitivity in the 3–79 keV energy range.

Until 2005 there were only seven known TeV blazars: Mrk 421, Mrk 501, 1ES 2344+514, PKS 2155–304, 1ES 1959+650, 1ES 1426+428, and PKS 2005-489. Thanks to the *Fermi* satellite and the ground-based TeV gamma-ray facilities (e.g., High Energy Stereoscopic System (H.E.S.S.), Major Atmospheric Gamma-Ray Imaging Cherenkov Telescopes (MAGIC)), Very Energetic Radiation Imaging Telescope Array System (VERITAS), and HAWC (High-Altitude Water Cherenkov Observatory) new TeV blazars have been discovered. In the TeV source catalog (TeVCat)\(^6\) the total number of blazars, at the time of writing, is 64 (HBLs = 48, IBLs = 8, LBLs = 2, FSRQs = 6), out of which *NuSTAR* has observed only 15 (HBLs = 11, IBLs = 2, FSRQs = 2). The main motivation of this work is to examine the X-ray intraday flux variability and the spectral shape of TeV HBLs in the energy range 3–79 keV. Blazar variability on IDV timescales is one of the most puzzling issues in the field, as it requires large energy outputs within small physical scales, and these emission regions are often very close to the supermassive black hole (SMBH). The blazars we study in the present work are relatively newly listed in the TeV catalog, and there is essentially no previous study of these sources in hard X-ray energies. Here, we present the first result of X-ray IDV and spectral studies of these TeV HBLs in the energy range 3–79 keV.

In our earlier work (Pandey et al. 2017) we examined the *NuSTAR* LCs of five TeV HBLs, 1ES 0229+200, Mrk 421, Mrk 501, 1ES 1959+650, and PKS 2155–304, for IDV. The *NuSTAR* spectra of these HBLs have been studied by other authors and found to be well described by either the simple PL or the curved LP model. For Mrk 421, see Sinha et al. (2015) and Baloković et al. (2016); for Mrk 501, see Furniss et al. (2015); for PKS 2155–304, see Madejski et al. (2016); and for 1ES 0229+200 and 1ES 1959+650, see Bhatta et al. (2017). In this work, we present the flux and spectral variability study of the remaining six TeV HBLs observed by *NuSTAR*: 1ES 0347–121, 1ES 0414+009, RGB J0710+591, 1ES 1101–232, 1ES 1218+304, and H 2356–309. We investigate the shapes of the hard X-ray spectra of these TeV HBLs using both single PL models and LP models. The structure of the paper is as follows. The observations and data processing are described in Section 2 and the data analysis techniques used to study the IDV flux variability and spectral shape of TeV blazars are discussed in Section 3. Section 4 presents the results of our study. Sections 5 and 6 include a detailed discussion and our conclusions, respectively.

2. Observations and Data Reduction

We downloaded all *NuSTAR* data sets that are publicly available from the HEASARC Data archive\(^5\) with good exposure times (those unaffected by passage through the South Atlantic Anomaly (SAA) or other periods of exceptionally high background) greater than 5 ks for these 6 blazars: 1ES 0347–121, 1ES 0414+009, RGB J0710+591, 1ES 1101–232, 1ES 1218+304, and H 2356–309. It turns out that there were only single such observations for each source and they were made between 2015 September 1 and 2016 May 18; the good exposure times ranged from 21.90 to 50.79 ks. Five out of six TeV HBLs were observed with *NuSTAR* in different guest observer programs on AGNs, but not as targets of opportunity, while H 2356–309 was observed in extragalactic surveys performed during the 2.5 years of the *NuSTAR* prime mission. The observing log of the *NuSTAR* data for these six HBL TeV blazars is given in Table 1.

The *NuSTAR* data were processed using HEASOFT\(^6\) version 6.19 and the updated Calibration Database (CALDB) files version 20161207. The calibration, cleaning, and screening of data were done using the standard *nupipeline* script with saamode=OPTIMIZED to correct for SAA passage. Each source LC and spectrum were extracted from a circular region centered at the source using the *nuproducts* script. Background data for each source were extracted from circular regions on the same detector module on which the source was focused but free from source contamination. The radii of the source and background regions that we used for the reduction of the data on our six TeV blazars are listed in Table 1; the brightest source, 1ES 1101–232, required a larger extraction radius than the others.

We summed the background-subtracted count rates of the two nearly identical *NuSTAR* detectors, FPMA and FPMB, and binned them in 5-minute intervals to generate the final light curves (LCs). The mean values of the difference between count rates between the FPMA and FPMB detectors were only $-0.004, 0.014, -0.015, -0.005, -0.006,$ and $-0.084$ for 1ES 0347–121, 1ES 0414+009, RGB J0710+591, 1ES 1101–232, 1ES 1218+304, and H 2356–309, respectively, and as all were essentially constant during the observations, a direct sum of the rates is justified. We used the same 5-minute bins in our earlier work Pandey et al. (2017), and using longer or shorter bins for different objects does not change the IDV LC patterns. The response files (rmf and arf files) were generated using the *numkrmf* and *numkarf* modules, respectively, within the *nuproducts* script.

3. Analysis Techniques

3.1. Fractional Variance

To estimate the amplitude of IDV in the LCs, we used the fractional variance, which is commonly used for examining X-ray LCs (e.g., Edelson et al. 2002; Vaughan et al. 2003; Wierzbolska & Siejkowski 2016) and defined as (see Pandey et al. 2017 for details)

$$F_{\text{var}} = \sqrt{\frac{S^2 - \sigma_{\text{err}}^2}{\bar{x}^2}}. \quad (1)$$

The uncertainty on $F_{\text{var}}$ is given by

$$\text{err}(F_{\text{var}}) = \sqrt{\left(\frac{\sigma_{\text{err}}^2}{2N\bar{x}^2F_{\text{var}}}\right)^2 + \left(\frac{\bar{x}^2}{N}\right)^2}, \quad (2)$$

\(^2\) http://tevcat.uchicago.edu
\(^5\) http://heasarc.gsfc.nasa.gov/docs/archive.html
\(^6\) http://heasarc.gsfc.nasa.gov/docs/nustar/analysis/
where $S^2$ is the sample variance, $\bar{x}$ is the arithmetic mean of the LC, $\sigma_{\text{err}}^2$ is the mean square error, and $N$ is the total number of data points in the LC. These values are given in Table 2, where dashes indicate that the sample variances were smaller than the respective errors. We consider strong evidence for variability to be present when $F_{\text{var}} > 3\sigma_{\text{err}}(F_{\text{var}})$.

### 3.2. Discrete Correlation Functions (DCFs)

We used a DCF analysis, introduced by Edelson & Krolik (1988), to search for correlations between LCs in two energy bands. The way in which we use the DCF is explained in detail in Pandey et al. (2017). When the DCF is applied to the same LC, it is called an autocorrelation function, ACF, which can give any timescale of variability present in the LC.

### 3.3. Hardness Ratio

The hardness ratio (HR) is a crude method of examining spectral variations. Given that earlier focusing X-ray telescopes have been restricted to exploring spectra only below 10 keV, we extracted LCs in two energy bands, here defining 3–10 keV as the soft band and 10–79 keV as the hard band. We then computed an HR, which is defined as

$$HR = \frac{(H - S)}{(H + S)},$$

and the error in HR ($\sigma_{HR}$) is calculated as

$$\sigma_{HR} = \frac{2}{(H + S)^{3/2}} \sqrt{(H^2\sigma_H^2 + S^2\sigma_S^2)},$$

where $S$ and $H$ are the net count rates in the soft (3–10 keV) and hard (10–79 keV) bands, respectively, while $\sigma_S$ and $\sigma_H$ are their respective errors.

### 3.4. Spectral Fitting

Our analysis of these NuSTAR spectra was done with XSPEC$^7$ version 12.9.0. We grouped each spectra to a minimum of 20 counts per bin using FTOOL grppha and then for each observation, the spectra of two NuSTAR instruments, FPMA and FPMB, were simultaneously fitted with two models via $\chi^2$ minimization. The first model we used for fitting is a PL:

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

where $\Gamma$ is the photon index, $F(E)$ is the flux at energy $E$, and $K$ is the normalization parameter (photons keV$^{-1}$ cm$^{-2}$ s$^{-1}$).

The second model we applied is the LP model. It is known that the X-ray spectra of many TeV HBLs are described well by the LP model (Massaro et al. 2004a; Tramacere et al. 2007a) defined as

$$F(E) = KE^{-\Gamma} (\alpha + \beta \log(E/E_{\text{pivot}}))^{-\gamma},$$

where the free parameters $\alpha$, $\beta$, and $K$ are the local photon index at fixed energy $E_{\text{pivot}} = 10$ keV, the spectral curvature, and the normalization parameter, respectively.

The effect of galactic absorption was taken into account by multiplying each model with a phabs component and taking fixed values of hydrogen column density, given in the second column of Table 3. The fitted model parameters for each model for all TeV HBLs are listed in Table 3. The errors for each parameter are estimated to a 90% confidence level ($\chi^2 = 2.706$). The model-fitted spectra, together with the data-to-model ratio for each of these six TeV HBLs, are plotted in Figure 4.

### 4. Results

#### 4.1. 1ES 0347–121

The TeV HBL 1ES 0347–121 ($\alpha_{2000} = 03^h49^m23^s$; $\delta_{2000} = -11^\circ58'38''$), at $z = 0.188$ (Woo et al. 2005), was first detected in the Einstein Slew Survey (Elvis et al. 1992) and

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7. https://heasarc.gsfc.nasa.gov/docs/xanadu/xspec/XspecManual.pdf
Table 3
Model Fits to the NuSTAR Spectra

| Blazar Name   | $n_H$ | Obs. ID | Power Law | Log-parabola ($E_{\text{pivot}} = 10$ keV) | Flux$_{3-79}$ keV | $F$-test | $p$-value |
|---------------|-------|---------|-----------|------------------------------------------|------------------|---------|----------|
|               |       |         | $\Gamma$  | $\chi^2$/dof ($\chi^2$)                  |                  |         |          |
|               |       |         |           |                                          |                  |         |          |
| IES 0347-121  | 3.05  | 60101036002 | 2.37 ± 0.06 | 154.74/169 (0.92) | 2.47 ± 0.10 | 0.37 ± 0.25 | 148.37/168 (0.88) | 0.68 ± 0.03 | 7.21 | 7.96 x 10^{-3} |
| IES 0414+009  | 8.51  | 60101035002 | 2.77 ± 0.06 | 164.66/182 (0.90) | 2.82 ± 0.10 | 0.16 ± 0.25 | 163.59/181 (0.90) | 0.71 ± 0.02 | 1.18 | 0.27 |
| RGB J0710+591 | 4.44  | 60101037004 | 2.27 ± 0.03 | 401.23/371 (1.08) | 2.34 ± 0.05 | 0.35 ± 0.13 | 380.84/370 (1.02) | 2.41 ± 0.06 | 19.81 | 1.13 x 10^{-5} |
| IES 1101−232  | 5.60  | 60101033002 | 2.50 ± 0.02 | 640.45/579 (1.11) | 2.59 ± 0.03 | 0.35 ± 0.08 | 584.09/578 (1.01) | 2.94 ± 0.07 | 55.78 | 3.02 x 10^{-13} |
| IES 1218+304  | 1.94  | 60101034002 | 2.55 ± 0.03 | 361.34/366 (0.99) | 2.67 ± 0.06 | 0.43 ± 0.15 | 336.76/365 (0.92) | 1.19 ± 0.03 | 26.64 | 4.03 x 10^{-7} |
| H 2356-309    | 1.44  | 60160840002 | 2.18 ± 0.03 | 349.67/357 (0.98) | 2.23 ± 0.04 | 0.27 ± 0.13 | 336.91/356 (0.95) | 2.81 ± 0.06 | 13.48 | 2.78 x 10^{-4} |

Notes.

a Galactic hydrogen column density in units of 10$^{20}$ cm$^{-2}$ taken from Kalberla et al. (2005).
b 3–79 keV unabsorbed flux for the best-fitted model in units of 10$^{-13}$ erg cm$^{-2}$ s$^{-1}$. 

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later classified as a BL Lac object (Schachter et al. 1993). It was discovered as a very-high-energy (VHE) γ-ray emitter with an integral flux (at $E > 250$ GeV) of $(3.9 \pm 1.1_{\text{stat}}) \times 10^{-12}$ cm$^{-2}$ s$^{-1}$ with HESS (Aharonian et al. 2007c).

*NuSTAR* observed 1ES 0347–121 on 2015 September 10 with a good exposure time of 32.93 ks. As seen from the LC, shown in Figure 1, the count rates are low and the data are noisy, so no detectable IDV is seen. We note that the *NuSTAR* count rates for all these TeV blazars are all less than 2 ct s$^{-1}$, whereas several of the set of 5 analyzed in Pandey et al. (2017) had means exceeding 5 ct s$^{-1}$. Hence, the ACF plot, shown in Figure 2, is also noisy, providing no useful information.

The soft and hard LCs (left panel), HR plot (middle panel), and the DCF plot between the soft and hard bands (right

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**Figure 1.** *NuSTAR* light curves of the TeV HBLs 1ES 0347–121, 1ES 0414+009, RGB J0710+591, 1ES 1101–232, 1ES 1218+304, and H 2356-309. The name of the blazar and the observation ID are given in each plot.

**Figure 2.** Autocorrelation plots for LCs of the TeV HBLs 1ES 0347–121, 1ES 0414+009, RGB J0710+591, 1ES 1101–232, 1ES 1218+304, and H 2356-309. The name of the blazar and the observation ID are given in each plot.
No significant spectral change is seen from the HR plot. We checked for variations quantitatively using a standard $\chi^2$ test,

$$\chi^2 = \sum_{i=1}^{N} \frac{(x_i - \bar{x})^2}{\sigma_i^2},$$

where $x_i$ is the HR value, $\sigma_i$ is its corresponding error, and $\bar{x}$ is the mean HR value. We considered a variation in the HR to be significant only if $\chi^2 > \chi^2_{99,\nu}$, where $\nu$ is the number of degrees of freedom (DoF) and the significance level is 0.99. These results are given for all these blazars in Table 4, where we see that for each source $\chi^2 < \chi^2_{99,\nu}$, so no significant spectral variations were detected.

The DCF plot is flat, which, in the presence of significant variations, would indicate no correlation between the two energy bands, but since no variations are detectable this type of DCF is expected.

Figure 3. Soft (3–10 keV, denoted by red filled circles) and hard (10–79 keV, denoted by black filled circles) LCs (left panels), hardness ratios (middle panels), and the discrete correlation functions between soft and hard LCs (right panels) of the blazars 1ES 0347−121, 1ES 0414+009, RGB J0710+591, 1ES 1101−232, 1ES 1218+304, and H 2356−309. The source names and observation IDs are given in the left panels.
The TeV blazar 1ES 0414+009 ($\alpha_{2000} = 04^h16^m53^s; \ell_{2000} = +01^\circ05'20'')$ is an HBL at $z = 0.287$ (Halpern et al. 1991). It was first detected in X-rays with the High Energy Astronomy Observatory (HEAO A-1) (Ulmer et al. 1980) and was classified as a BL Lac object by Ulmer et al. (1983). It was observed above 200 GeV by VERITAS with source flux equal to $(5.2 \pm 1.1_{\text{stat}} \pm 2.6_{\text{sys}}) \times 10^{-12}$ photons cm$^{-2}$ s$^{-1}$ (Aliu et al. 2012). 1ES 0414+009 was observed with NuSTAR on 2015 November 25 with a good exposure time of 34.16 ks. The 3–79 keV LC of 1ES 0414+009 is shown in Figure 1. The data are both noisy and sparse, resulting in no significant IDV detection, which is consistent with the value of fractional variance given in Table 2. Consequently, the ACF plot, given in Figure 2, does not show any hint of variability timescale.

The soft and hard LCs of 1ES 0414+009 are plotted in the left panel of Figure 3. The HR plot in the middle panel of that figure reveals no significant spectral variations (also see Table 4) and the DCF plot shown in the right panel of Figure 3 again is flat.

The high-frequency-peaked BL Lacertae object RGB J0710+591 ($\alpha_{2000} = 07^h10^m26^s; \ell_{2000} = +59^\circ09'00''$) is located at a redshift of $z = 0.125$ (Giommi et al. 1991) and also was first detected by HEAO A-1 (Wood et al. 1984). It was detected with VERITAS with the integral flux (above 300 GeV) recorded to be $(3.9 \pm 0.8) \times 10^{-12}$ cm$^{-2}$ s$^{-1}$ (Acciari et al. 2010).

NuSTAR observed RGB J0710+591 on 2015 September 1 for 26.48 ks. As seen from the LC in Figure 1 the source is somewhat brighter, by a factor of $\sim 3$, than the two discussed above, and there is a hint of variability. However, the data are still noisy and no significant intraday variations are found, as shown by the value of $F_{\text{var}}$. The ACF of RGB J0710+591, shown in Figure 2, provides no evidence of an IDV timescale.

The soft and hard LCs (left panel), HR plot (middle panel), and the DCF plot of RGB J0710+591 are shown in Figure 3. Given that both the soft and hard LCs are noisy, it is not surprising that the HR plot does not show any detectable spectral variations (Table 4) and the DCF plot between the soft and hard band LCs is steady within the noise.

The TeV HBL 1ES 1101–232 ($\alpha_{2000} = 11^h03^m36^s5; \ell_{2000} = -23^\circ29'45''$), at $z = 0.186$ (Remillard et al. 1989), was discovered in the Einstein Slew Survey (Perlmutter et al. 1996). Aharonian et al. (2007b) reported the discovery of VHE $\gamma$-ray emission from 1ES 1101–232 with integral flux (above 200 GeV) of $(4.5 \pm 1.2) \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$.

1ES 1101–232 was observed with NuSTAR for 50.79 ks on 2016 January 12. This was the brightest of our blazars from this sample, at the time of its NuSTAR observation, and the LC in Figure 1 appears to show significant flux variations in the energy range 3–79 keV. The value of $F_{\text{var}}$ for that full energy range given in Table 2 confirms the presence of IDV. The $F_{\text{var}}$ values for the soft and hard NuSTAR bands, also given in Table 2, confirm that the variations are present in both these energy bands. Despite the presence of significant variability, the ACF plot of 1ES 1101–232 in Figure 2 is almost flat, providing no variability timescale.

The soft and hard LCs (left panel), HR (middle panel), and the DCF for 1ES 1101–232 are plotted in Figure 3. The HR plot of 1ES 1101–232 reveals no detectable spectral variations, nor is significant correlation observed from the DCF plot, despite the presence of variability. In this case, these flat curves provide some evidence that the emission mechanism is the same for both bands.

1ES 1218+304 ($\alpha_{2000} = 12^h21^m26^s3; \ell_{2000} = +30^\circ11'29''$) is an HBL located at a redshift of $z = 0.182$ (Véron-Cetty & Véron 2003). Sato et al. (2008) reported a flux over $2–10$ keV range $\sim 2.0 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ and recently, an integrated flux of $3.33 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ in the $0.3–10$ keV range was reported by Wierzcholska & Wagner (2016). The TeV flux ($E > 200$ GeV) of $(12.2 \pm 2.6) \times 10^{-12}$ cm$^{-2}$ s$^{-1}$ from 1ES 1218+304 was observed with VERITAS (Acciari et al. 2009).

NuSTAR observed 1ES 1218+304 with a good exposure time of 49.55 ks on 2015 November 23. The LC and ACF plots of 1ES 1218+304 are shown in Figure 1 and Figure 2, respectively. As seen from the LC, 1ES 1218+304 appears to show clear intraday variations that are confirmed by the $F_{\text{var}}$ value given in Table 2. The variations are clearly present in the soft band but not obvious in the hard band, with its much lower fluxes. The ACF plot indicates a possible IDV timescale of $\sim 23.5$ ks.

The soft and hard LCs of 1ES 1218+304 are plotted in the left panel of Figure 3. The HR plot in the middle panel of that figure seems to show some fluctuations but is quite noisy, providing no useful information. The DCF plot shown in the right panel of Figure 3 shows no correlations, as expected from the lack of significant variability in the hard band.

H 2356–309

H 2356–309 ($\alpha_{2000} = 23^h35^m50^s4; \ell_{2000} = -30^\circ37'23''$), located at a redshift of $z = 0.165$ (Falomo 1991), was first detected at X-rays by the Uhuru satellite (Forman et al. 1978), and subsequently by HEAO A-1 (Wood et al. 1984). The X-ray (up to $\sim 50$ keV) spectrum of H 2356–309 was characterized by a broken PL with a synchrotron peak at $1.8 \pm 0.4$ keV during BeppoSAX observations (Costamante et al. 2001). It was detected by H.E.S.S. with an integral flux (above 240 GeV) of $(3.06 \pm 0.26_{\text{stat}} \pm 0.61_{\text{syst}}) \times 10^{-12}$ cm$^{-2}$ s$^{-1}$ (H.E.S.S. Collaboration et al. 2010).

H 2356–309 was observed with NuSTAR for a relatively short good time exposure of 21.90 ks on 2016 May 18. As seen from the LC in the Figure 1 the source had count rates nearly as high as 1ES 1101–232 and shows hints of variability.
However, the data are both noisier and sparser, and the $F_{\text{var}}$ value is consistent with no significant IDV. As a result, the ACF shown in Figure 2 shows no IDV timescale.

The soft and hard LCs (left panel), HR plot (middle panel), and the DCF plot (right panel) of H 2356–309 are shown in Figure 3. The HR plot reveals no significant spectral variation in the *NuSTAR* range. The DCF plot is flat.

5. Discussion
5.1. Constraints on Physical Parameters from X-Ray Variability

TeV blazars observed for sufficient times are known to exhibit strong variability with large amplitudes at all frequencies. Flux variations are understood to predominantly originate from the Doppler-boosted relativistic jets (Marscher 2014; Calafut & Wiita 2015); however, in very low states, the instabilities or hot spots on the accretion disk can also produce variations on IDV and STV timescales (Chakrabarti & Wiita 1993; Mangalam & Wiita 1993). At high energies (X-rays to $\gamma$-rays) the variations are often found to be very rapid, indicating compact emitting regions (Cui 2004; Aharonian et al. 2007a; Albert et al. 2007; Pandey et al. 2017). The hard X-ray variability of $\sim$14 minutes detected in the *NuSTAR* LCs of Mrk 421 (Paliya et al. 2015) were explained in terms of magnetic reconnections accelerating particles to ultrarelativistic velocities in compact regions within relativistic jets (“jets-in-a-jet” model; Giannios et al. 2009).

For these six, not extremely bright sources, we found a likely variability timescale for only one TeV HBL, 1ES 1218+304. The spectra clearly indicate that the dominant origin of hard X-rays in TeV HBLs is the high-energy tail of the synchrotron emission. The synchrotron cooling timescale in the observer’s frame is (e.g., Pandey et al. 2017)

$$t_{\text{cool}}(\gamma) \approx 7.74 \times 10^8 \frac{(1 + z)}{\delta} B^{-2} \gamma^{-1} \text{s},$$

where $\delta$ is the bulk Doppler factor, $B$ is the magnetic field strength in Gauss (G), and $\gamma$ is the electron Lorentz factor.

In the *NuSTAR* energy range the synchrotron frequency is (e.g., Pandey et al. 2017)

$$\nu \approx \nu_{19} \times 10^{19} \text{Hz} \simeq 4.2 \times 10^6 \frac{\delta}{1 + z} B \gamma^2,$$

where $0.08 < \nu_{19} < 2$. We eliminate $\gamma$ from Equations (8) and (9) and use the fact that the cooling timescale must be smaller than or equal to the observed minimum variability timescale, to estimate for 1ES 1218+304 ($t_{\text{var}} = 23510$ s, $z = 0.182$ and $\delta \simeq 20$; e.g., Sato et al. 2008) that

$$B \geq 0.03 \nu_{19}^{-1/3} \text{G}.$$  

Using Equation (9) we can constrain the electron Lorentz factor to

$$\gamma \leq 2.16 \times 10^6 \nu_{19}^{2/3}.$$  

For $\nu_{19} = 1$, we get $B \geq 0.03 \text{ G}$ and $\gamma \leq 2.16 \times 10^6$.

The characteristic size of the emitting region also can be estimated as

$$R \leq c t_{\text{var}}(1 + z) \leq 1.19 \times 10^{16} \text{cm}.$$  

These values are close to those obtained by Sato et al. (2008).

The maximum energy of photons produced by the electrons via Compton scattering (in the Thomson limit) can be estimated to be

$$E_{\text{max}} \simeq \delta \gamma_{\text{max}} m_e c^2 \sim 19 \nu_{19}^{2/3} \text{ TeV.}$$  

5.2. Correlation between Emissions in Soft and Hard Energy Bands

We searched for any possible correlation between the soft (3–10 keV) and hard (10–79 keV) band X-ray emissions for each TeV HBL using the DCF. The X-ray emissions in different energy bands are known to be generally well correlated (Zhang et al. 2006; Pandey et al. 2017). However, in our analysis the DCF plots, shown in the right panel of Figure 3, are almost flat, indicating either of two possibilities. The first is that the X-ray emissions in these two energy bands are actually uncorrelated, which could indicate that the soft and hard X-ray emissions are plausibly produced by different electron populations. The second and more likely interpretation for the lack of correlations here is that the data are too noisy, particularly in the low-flux, hard X-ray LCs, to reveal the actual probable correlations between these bands for these sources.

5.3. X-Ray Spectra

We have calculated the unabsorbed 3–79 keV fluxes for each of these six HBLs, and they are given, with errors, in Table 3. They were determined using the $cflux$ routine of *XSPEC*. The maximum flux observed is $\sim 2.94 \times 10^{-11} \text{erg cm}^{-2} \text{s}^{-1}$ for 1ES 1101–232, while the flux was least, at $\sim 0.68 \times 10^{-11} \text{erg cm}^{-2} \text{s}^{-1}$, for 1ES 0347–121.

We performed simple HR analyses to search for spectral variations in the *NuSTAR* energy range. In general, it has been found that for TeV HBLs the HR increases with increasing count rates, a behavior called “harder when brighter” (e.g., Brinkmann et al. 2003; Ravasio et al. 2004; Pandey et al. 2017). But in our current study we observed that the HR plots for all six TeV HBLs, shown in the middle panels of Figure 3, do not show any significant variations. This indicates that during these observations we could not detect any variability of the X-ray spectra of these HBLs (Zhang 2008). Again, this negative result could easily arise from the low count rates for these blazars.

We performed spectral fits using *XSPEC* to study the shape of these TeV blazar spectra in the 3–79 keV energy range, as displayed in Figure 4. We first applied the simple PL model, which has a photon index ($\Gamma$) and the normalization as the two free parameters. As suggested by several studies, the X-ray spectra of HBLs are curved and described well with the LP model. The LP model has three free parameters: the photon index ($\Gamma$) and the normalization parameter. In this case the photon index is not a constant and varies along with the logarithm of the energy (see Equation (6)).

To examine any improvement in the fit using the LP over the PL model, we performed F-tests where the null hypothesis is that the simpler, PL model provides the better fit. We found that for five out of six HBLs the curved LP model provides a better fit over the simple PL, as can be seen from the high...
Figure 4. *NuSTAR* spectra (black points are for FPMA and red points are for FPMB) of six TeV HBLs, with the best-fitting model in the upper panels and the ratios (data/model) for both the models tested, in the bottom two panels. The blazar name, observation ID, and the type of best-fitting model (LP or PL) are given in each plot.
F-statistic values and the corresponding probability (>99%) given in Table 3. Only in the case of 1ES 0414+009 does a steep PL with photon index 2.77 provide an equivalently good fit. The NuSTAR spectra of the other five TeV BL Lac objects 1ES 0347−121, RGB J0710+591, 1ES 1101−232, 1ES 1218+304, and H 2356−309 are well described by LP models with α lying in the range 2.23−2.67 and the spectral curvature β ≃ 0.27−0.43.

The shape of the X-ray spectra of TeV BL Lacs provides us with valuable information about the distribution of emitting particles and the particle acceleration mechanism. The curvature of X-ray spectra of BL Lac objects can be understood in terms of an energy-dependent particle acceleration probability and the subsequent radiative cooling (Massaro et al. 2004a). Thus, this study of the nature of X-ray spectra of TeV BL Lac objects may be used to understand the particle acceleration in these blazars. Concave X-ray spectra of some TeV BL Lacs have been reported in some studies (e.g., Zhang 2008) and they were interpreted as a mixture of the high-energy tail of the synchrotron emission and the low-energy portion of the IC emission. However, we did not find any signature of an IC component in our X-ray spectral analysis, indicating that the hard X-ray spectra of TeV BL Lacs are dominated by synchrotron emission.

6. Conclusions

We examined the archival individual NuSTAR LCs of the six TeV BL Lac objects that we had not previously analyzed (Pandey et al. 2017) for IDV and also searched for possible variability timescales using discrete autocorrelation analyses. The X-ray count rates were quite low for these TeV BL Lacs and none of the exposure times exceeded 51 ks, so it should not be surprising that we found significant IDV only in the LCs of two of the six TeV BL Lacs, 1ES 1101−232 and 1ES 1218+304.

Using ACFs, we found a hint of the presence of a variability timescale in the LC of only 1ES 1218+304. For the other five LCs, the ACF plots are noisy. Using that apparent observed variability timescale, we estimated (for νν = 1) the magnetic field strength (B ≈ 0.3 G), electron Lorentz factor (γ ≈ 2.2 × 10⁶), and emission region size (R ≈ 1.2 × 10⁹ cm) for 1ES 1218+304.

We used an HR analysis to make a preliminary study of the X-ray spectral variability of these six TeV BL Lacs. We found no significant variation in HR with time for each TeV HBL, indicating no detectable spectral variability was present during these observations. We also performed DCF analyses to search for any correlations between soft (3−10 keV) and hard (10−79 keV) NuSTAR bands. The DCF plot for each TeV HBL is almost flat, indicating either that no significant correlation was present between the two energy bands, or, more likely, that the harder fluxes were too low to allow for any such correlations to be detected.

The spectral shape of 1ES 0414+009 can be well fit with a PL. The NuSTAR spectra of the remaining five HBLs, 1ES 0347−121, RGB J0710+591, 1ES 1101−232, 1ES 1218+304, and H 2356−309, are clearly curved and require log-parabolic fits.

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ORCID iDs
Ashwani Pandey © https://orcid.org/0000-0003-3820-0887
Alok C. Gupta © https://orcid.org/0000-0002-9331-4388
Paul J. Wiita © https://orcid.org/0000-0002-1029-3746

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