X-ray Intraday Flux and Spectral Variability of TeV Blazars with *NuSTAR*

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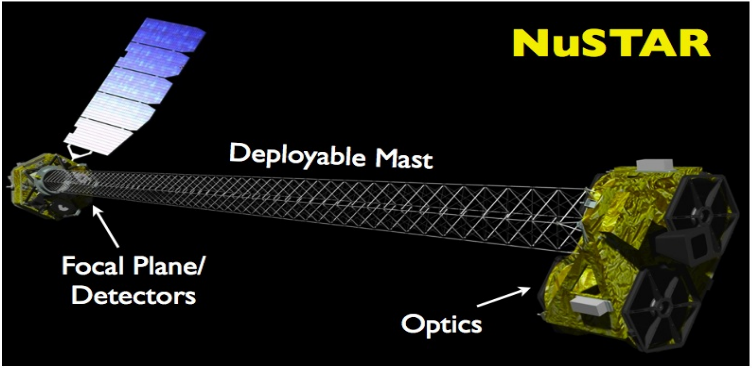
Pandey et al. 2017, ApJ, 841, 123.
Pandey et al. 2018, ApJ, 859, 49.

Introduction

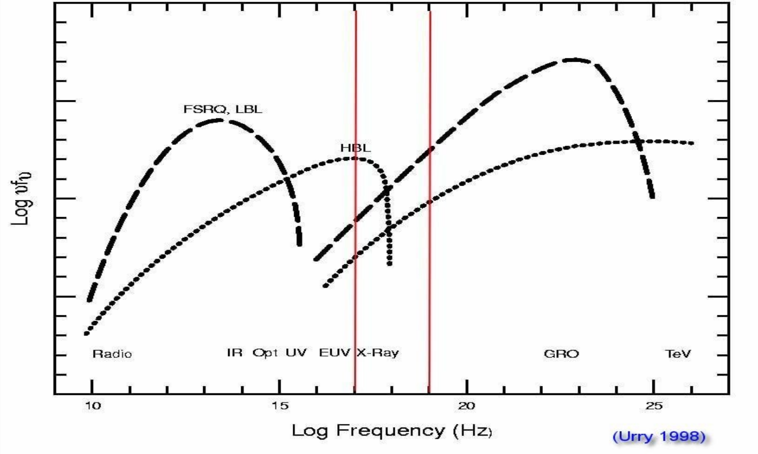
Nuclear Spectroscopic Telescope Array (NuSTAR) is the first focusing **hard X-ray (3–79 keV)** telescope.



Two detector modules : FPMA and FPMB

Angular resolution : 18″ FWHM

Spectral resolution : 400/900 eV at 10/68 keV


FSRQ, LBL
HBL
Log νfν
Radio
IR Opt UV
EUV X-Ray
GRO
TeV
10
15
20
25
Log Frequency (Hz)
(Urry 1998)

Total number of TeV blazars : 66[1] (HBLs = 49, IBLs = 8, LBLs = 2, FSRQs = 7).
NuSTAR has observed only 15 TeV blazars (**HBLs = 11**, IBLs = 2, FSRQs = 2).

[1] `http://tevcat.uchicago.edu`

Observations and Data Reduction

We downloaded all *NuSTAR* data sets that are publicly available from the HEASARC Data archive[2] with good exposure times greater than 5 ks for 11 TeV HBLs.

The calibration, cleaning and screening of data were done using the standard **nupipeline** script, and the light curves and spectra were extracted using the **nuproducts** script.

Source/background radii : **30″–40″**

[2] `http://heasarc.gsfc.nasa.gov/docs/archive.html`

Total observations : 46

1ES 0229+200 : 3

Mrk 421 : 22

Mrk 501 : 4

1ES 1959+650 : 2

PKS 2155−304 : 9

1ES 0347−121 : 1

1ES 0414+009 : 1

RGB J0710+591: 1

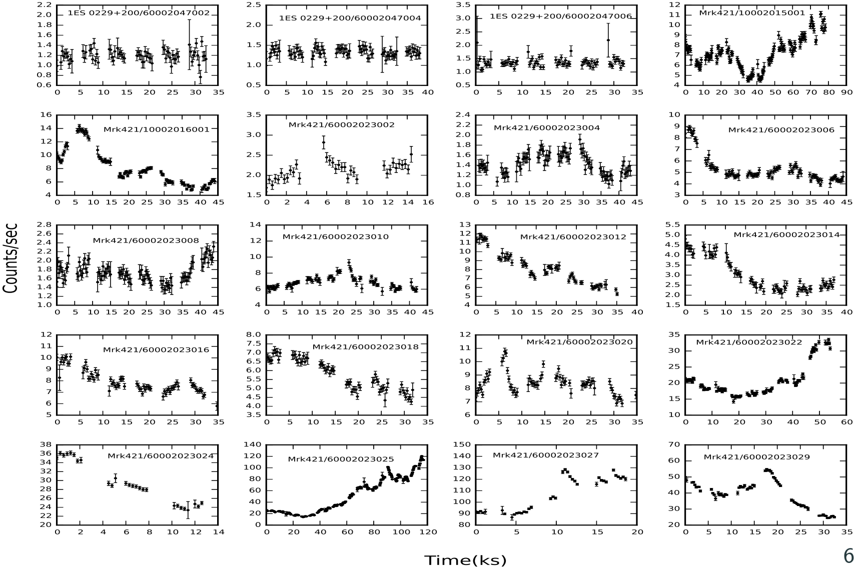
1ES 1101−232 : 1

1ES 1218+304 : 1

H 2356−309 : 1

These 46 observations were made between 7 July 2012 and 2016 May 18 and the good exposure times ranged between 5.76 ks to 57.51 ks.

Sample Light Curves :



Analysis Techniques

Flux Variability

Soft (S) band : **3-10 keV** Hard (H) band : **10-79 keV**

Fractional Variance (Vaughan et al. 2003):

$$\mathbf{F_{var}} = \sqrt{\frac{\mathbf{S^2} - \overline{\sigma^2_{\mathbf{err}}}}{\bar{\mathbf{x}}^2}}. \tag{1}$$

The uncertainty on F_{var} is given by

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

where S^2 is the sample variance, $\bar{x}$ is the arithmetic mean of the LC, $\overline{\sigma^2_{err}}$ is the mean square error, and N is the total number of data points in the LC.

Spectral Variability

Hardness Ratio (HR) :

$$\mathbf{HR} = \frac{(\mathbf{H} - \mathbf{S})}{(\mathbf{H} + \mathbf{S})}, \tag{3}$$

and the error in HR (σ_{HR}) is calculated as

$$\sigma_{\mathbf{HR}} = \frac{\mathbf{2}}{(\mathbf{H} + \mathbf{S})^{\mathbf{2}}} \sqrt{(\mathbf{H}^{\mathbf{2}}\sigma_{\mathbf{S}}^{\mathbf{2}} + \mathbf{S}^{\mathbf{2}}\sigma_{\mathbf{H}}^{\mathbf{2}})}, \tag{4}$$

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

- **Spectral fitting :**
  - Single Power-law Model (*const*pha(po)*):

$$\mathbf{F(E) = KE^{-\Gamma}} \tag{5}$$

  - Log-parabola Model (*const*pha*logpar*)(Massaro et al. 2004a):

$$\mathbf{F(E) = K(E/E_{pivot})^{-(\alpha+\beta \log(E/E_{pivot}))}} \tag{6}$$

    $E_{pivot} = 10$ keV
  - **const** factor is to account for the cross-calibration uncertanties (5%; Madsen et al. 2015) between FPMA and FPMB.
  - **pha** factor is to account for galactic absorption.
  - **cflux** routine is used to estimate the flux.

Discrete Correlation Function (Edelson & Krolik 1988):

$$\mathbf{UDCF_{ij}} = \frac{(\mathbf{x_i} - \bar{\mathbf{x}})(\mathbf{y_j} - \bar{\mathbf{y}})}{\sigma_{\mathbf{x}}\sigma_{\mathbf{y}}} \tag{7}$$

Each of these is associated with the pairwise lag $\Delta t_{ij} = t_j - t_i$.

$$\mathbf{DCF}(\tau) = \frac{\mathbf{1}}{\mathbf{M}} \sum \mathbf{UDCF_{ij}}. \tag{8}$$

such that, $\tau - \delta/\mathbf{2} \leq \mathbf{t_j} - \mathbf{t_i} < \tau + \delta/\mathbf{2}$

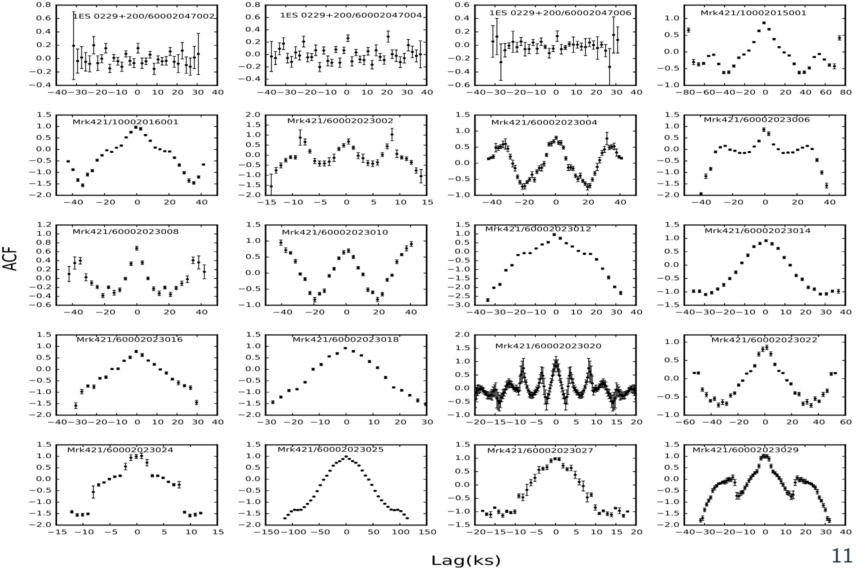
The standard error for each bin is defined as

$$\sigma_{\mathbf{DCF}}(\tau) = \frac{\sqrt{\sum[\mathbf{UDCF_{ij}} - \mathbf{DCF}(\tau)]^2}}{\mathbf{M} - \mathbf{1}}. \tag{9}$$

When $x = y$, we obtain the auto-correlation function (ACF).

Results

Sample ACF plots :

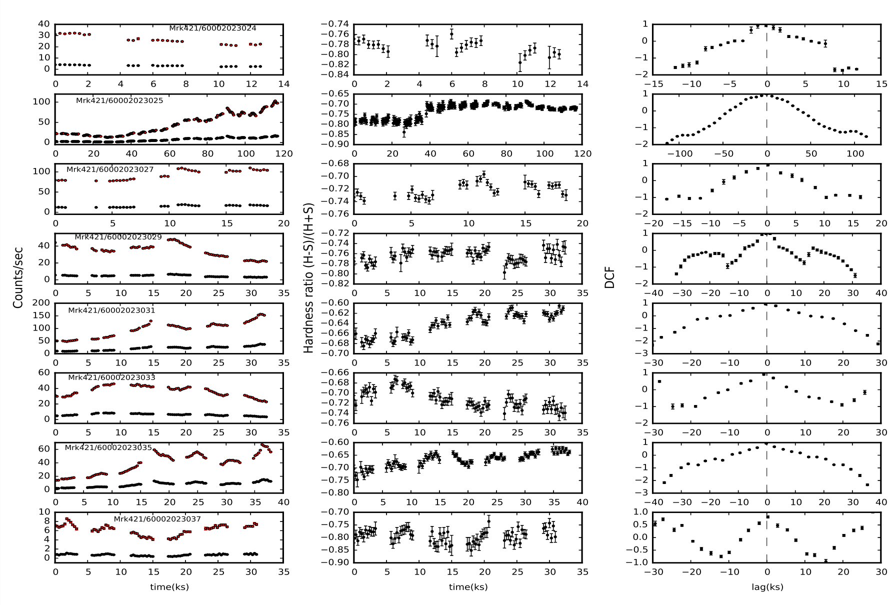


X-ray variability parameters.

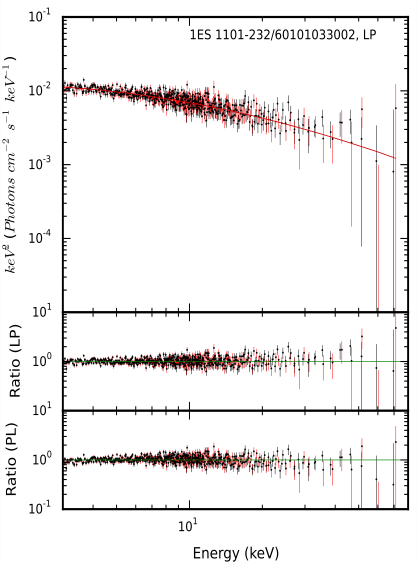
Blazar Name	Obs. ID	$F_{var}(percent)$			ACF(ks)	Bin-size(ks)
		Soft (3-10 keV)	Hard (10-79 keV)	Total (3-79 keV)		
1ES 0229+200	60002047002	-	15.632 ± 4.757	-	-	2.00
	60002047004	-	-	-	-	2.00
	60002047006	8.638 ± 2.557	-	4.460 ± 3.411	-	2.00
MRK 421	10002015001	21.105 ± 0.341	26.899 ± 1.179	21.217 ± 0.260	-	5.00
	10002016001	31.225 ± 0.337	48.503 ± 1.227	32.314 ± 0.305	-	3.00
	60002023002	7.531 ± 1.183	68.747 ± 8.125	9.159 ± 1.029	4.9	0.90
	60002023004	12.173 ± 0.874	75.723 ± 13.099	11.485 ± 0.860	19.9	1.50
	60002023006	20.051 ± 0.402	39.626 ± 1.695	21.595 ± 0.392	11.4	3.00
	60002023008	13.566 ± 0.721	31.496 ± 9.967	10.275 ± 0.757	-	3.50
	60002023010	10.371 ± 0.517	8.027 ± 3.382	10.264 ± 0.411	19.5	3.00
	60002023012	20.310 ± 0.463	33.744 ± 1.475	21.556 ± 0.424	-	3.00
	60002023014	25.203 ± 1.219	21.537 ± 11.947	26.702 ± 0.652	-	3.00
	60002023016	12.497 ± 0.550	13.995 ± 2.175	11.815 ± 0.421	-	3.00
	60002023018	14.707 ± 0.453	14.930 ± 2.339	14.583 ± 0.420	-	3.00
	60002023020	10.217 ± 1.284	-	9.164 ± 0.374	2.5	0.30
	60002023022	22.052 ± 0.386	40.386 ± 1.243	24.265 ± 0.193	32.8	3.00
	60002023024	15.181 ± 0.431	17.344 ± 1.401	15.458 ± 0.411	-	1.00
	60002023025	59.837 ± 0.131	64.919 ± 0.351	60.497 ± 0.123	-	6.00
	60002023027	13.406 ± 0.196	17.386 ± 0.486	13.945 ± 0.182	-	1.00
	60002023029	25.285 ± 0.184	26.116 ± 0.517	22.266 ± 0.175	13.1	1.00
	60002023031	31.141 ± 0.108	36.316 ± 0.229	32.073 ± 0.098	-	2.00
	60002023033	19.344 ± 0.540	25.137 ± 0.458	18.747 ± 0.169	-	2.00
	60002023035	39.043 ± 0.178	44.841 ± 0.427	39.943 ± 0.165	-	2.00
	60002023037	17.584 ± 0.404	24.000 ± 1.382	18.268 ± 0.387	12.6	1.00
	60002023039	12.310 ± 0.460	17.255 ± 1.798	12.773 ± 0.443	-	2.00

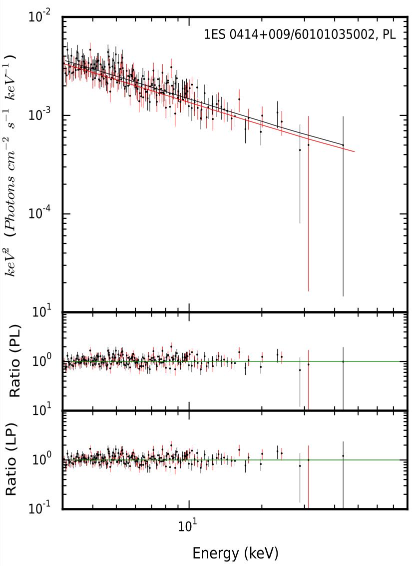
X-ray variability parameters.

Blazar Name	Obs. ID	$F_{var}(percent)$			ACF(ks)	Bin-size(ks)
		Soft (3-10 keV)	Hard (10-79 keV)	Total (3-79 keV)		
MRK 501	60002024002	1.327 ± 1.406	-	1.391 ± 1.121	-	1.00
	60002024004	14.572 ± 0.627	20.901 ± 1.940	15.540 ± 0.354	-	5.00
	60002024006	4.278 ± 0.432	5.138 ± 0.925	3.743 ± 0.351	-	2.00
	60002024008	6.338 ± 0.670	9.067 ± 1.400	8.284 ± 0.358	8.0	1.00
1ES 1959+650	60002055002	26.849 ± 1.192	35.449 ± 2.876	26.629 ± 0.451	-	3.00
	60002055004	-	6.522 ± 2.963	-	-	1.00
PKS 2155-304	10002010001	12.901 ± 0.915	33.771 ± 5.960	10.601 ± 0.744	29.6	2.00
	60002022002	-	21.275 ± 5.478	11.020 ± 1.109	57.4	5.00
	60002022004	12.551 ± 2.437	21.333 ± 7.654	14.931 ± 1.400	-	3.00
	60002022006	10.830 ± 4.268	-	9.256 ± 2.162	-	2.00
	60002022008	-	28.233 ± 15.966	13.504 ± 3.000	-	3.00
	60002022010	-	12.931 ± 15.148	-	-	3.00
	60002022012	20.963 ± 1.300	24.613 ± 3.958	20.916 ± 1.160	-	4.00
	60002022014	16.726 ± 2.082	-	16.992 ± 1.554	-	4.00
	60002022016	16.810 ± 2.876	-	3.298 ± 8.251	-	2.00
1ES 0347−121	60101036002	−	−	−	-	1.00
1ES 0414+009	60101035002	−	−	5.72 ± 3.73	-	1.00
RGB J0710+591	60101037004	−	−	−	-	1.00
1ES 1101−232	60101033002	4.24 ± 1.10	9.08 ± 2.81	3.94 ± 0.99	-	2.00
1ES 1218+304	60101034002	7.30 ± 1.84	7.28 ± 8.70	7.62 ± 1.49	23.51	1.50
H 2356−309	60160840002	−	−	2.10 ± 3.40	-	1.00


Mrk421/60002023024
Mrk421/60002023025
Mrk421/60002023027
Mrk421/60002023029
Mrk421/60002023031
Mrk421/60002023033
Mrk421/60002023035
Mrk421/60002023037
Counts/sec
Hardness ratio (H-S)/(H+S)
DCF
time(ks)
time(ks)
lag(ks)

Sample *NuSTAR* spectra :





Model fits to the NuSTAR spectra :

Blazar Name	Power Law		Log-parabola ($E_{pivot} = 10$ keV)			$Flux^{(2)}_{3-79keV}$	F-test	p-value
	Γ	$\chi^2/dof(\chi^2_r)$	α	β	$\chi^2/dof(\chi^2_r)$			
1ES 0347-121	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	7.96×10^{-3}
1ES 0414+009	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	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	1.13×10^{-5}
1ES 1101−232	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	3.02×10^{-13}
1ES 1218+304	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	4.03×10^{-7}
H 2356-309	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	2.78×10^{-4}

(2) 3−79 keV unabsorbed flux for best fitted model in the units of 10^{-11} erg cm^{-2} s^{-1}

Mrk 421 : Sinha et al. (2015), Balokovi et al. (2016)

Mrk 501 : Furniss et al. (2015)

PKS 2155-304 : Madejski et al. (2016), Bhatta et al. (2017)

1ES 0229+200 : Bhatta et al. (2017)

1ES 1959+650 : Bhatta et al. (2017)

Discussion

Constraints on Physical Parameters from X-ray Variability :

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

$$\nu \equiv \nu_{19} \times 10^{19}\mathrm{Hz} \simeq 4.2 \times 10^{6} \frac{\delta}{1+z} B\gamma^{2}, \quad (11)$$

where $0.08 < \nu_{19} < 2$ for X-rays in the *NuSTAR* band. Using the fact that the cooling timescale must be smaller than or equal to the observed minimum variability timescale, for Mrk 421 (with our minimum $t_{var} = 2500$ s and $z = 0.031$),

$$B \geq 0.35\ \delta^{-1/3}\nu_{19}^{-1/3}\mathrm{G}. \quad (12)$$

For a $\delta = 25$, we find $B \geq 0.12\nu_{19}^{-1/3}$ G, which is close to the typical value of $B \sim 0.1$ G that is inferred from the SED modeling of Mrk 421.

Assuming $\delta = 25$ and $\mathbf{B \geq 0.12}$ G, we can constrain the electron Lorentz factor to

$$\gamma \leq 9 \times 10^5 \nu_{19}^{1/2}. \tag{13}$$

We can also estimate the characteristic size of the emitting region as

$$R \leq ct_{var}\delta/(1+z) \leq 1.8 \times 10^{15} cm. \tag{14}$$

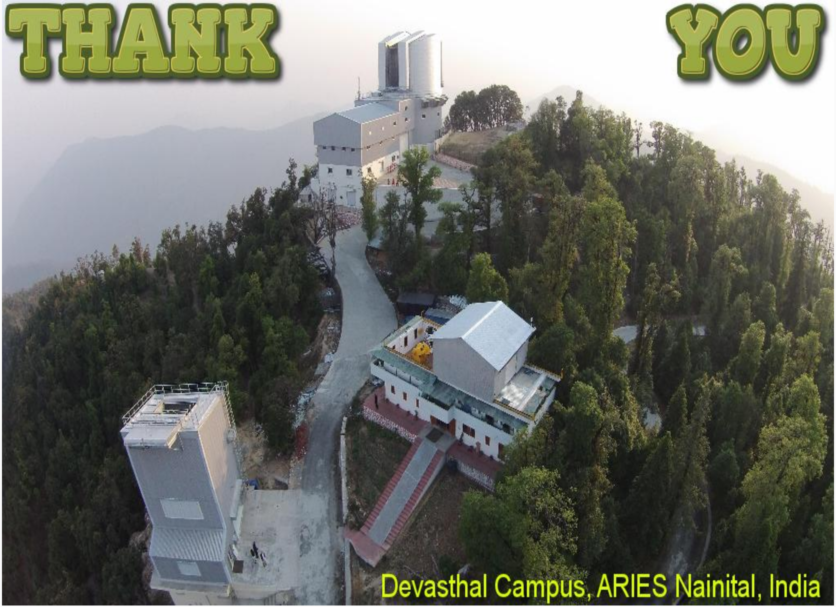
Table 1: Constraints on Physical Parameters.

Blazar	t_{var}(s)	δ	B (G)	γ	R (cm)
Mrk 421	2500	25	≥ 0.12	$\leq 9.0 \times 10^5$	$\leq 1.8 \times 10^{15}$
Mrk 501	8000	15	≥ 0.07	$\leq 1.5 \times 10^6$	$\leq 3.5 \times 10^{15}$
PKS 2155−304	29600	30	≥ 0.02	$\leq 2.0 \times 10^6$	$\leq 2.4 \times 10^{16}$
1ES 1218+304	23510	20	≥ 0.03	$\leq 2.2 \times 10^6$	$\leq 1.2 \times 10^{16}$

Summary

- We have found strong evidence of IDV for: Mrk 421, in all 22 of 22 LCs; Mrk 501, in 3 of 4; 1ES 1959+650, in 1 of 2; PKS 2155–304, in 7 of 9; 1ES 1101−232, in 1 of 1; and 1ES 1218+304 in 1 of 1.
- Using ACFs, we found evidence for timescales ranging from 2.5 to 32.8 ks in eight LCs of Mrk 421, a timescale of 8.0 ks for one LC of Mrk 501, 29.6 and 57.4 ks timescales for two LCs of PKS 2155–304, and 23.51 ks timescale for the LC of 1ES 1218+304.
- Using the shortest observed variability timescales, we estimated the values of magnetic field (B), electron Lorentz factor (γ), and size (R) of the emitting regions.

- We found that the X-ray spectra harden with increasing count rates for Mrk 421 and Mrk 501.
- We found overall positive correlations with zero lag for Mrk 421 (in all 22 observations), for Mrk 501 (in 3 of 4), for 1ES 1959+650 (in 1 of 2), and for PKS 2155–304 (in 3 of 9). These measurements indicate that the hard and soft X-ray emissions from these blazers are produced by the same populations of electrons.
- The spectral shape of 1ES 0414+009 can be well fit with a PL. The NuSTAR spectra of the five HBLs, 1ES 0347-121, RGB J0710+591, 1ES 1101-232, 1ES 1218+304, and H 2356-309, are clearly curved and require logparabolic fits.


THANK
YOU
Devasthal Campus, ARIES Nainital, India