X-ray Intraday Variability of the TeV Blazar Mrk 421 with Chandra

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ABSTRACT

We present an extensive study of 72 archival Chandra light curves of the high-frequency-peaked type blazar Mrk 421, the first strong extragalactic object to be detected at TeV energies. Between 2000 and 2015 Mrk 421 often displayed intraday variability in the 0.3-10.0 keV energy range, as quantified through fractional variability amplitudes that range up to 21.3 per cent. A variability duty cycle of $\sim 84$ per cent is present in these data. Variability timescales, with values ranging from 5.5 to 30.5 ks, appear to be present in seven of these observations. Discrete correlation function analyses show positive correlations between the soft (0.3–2.0 keV) and hard (2.0–10.0 keV) X-ray energy bands with zero time lags, indicating that very similar electron populations are responsible for the emission of all the X-rays observed by Chandra. The hardness ratios of this X-ray emission indicate a general “harder-when-brighter” trend in the spectral behaviour of Mrk 421. Spectral index–flux plots provide model independent indications of the spectral evolution of the source and information on the X-ray emission mechanisms. Brief discussions of theoretical models that are consistent with these observations are given.

Key words: galaxies: active — BL Lacertae objects: general — BL Lacerate objects: individual: Mrk 421

1 INTRODUCTION

An active galactic nucleus (AGN) involves a supermassive black hole (SMBH), fueled by an accretion disc, producing a variety of highly energetic phenomena (Rees 1984). When a radio-loud AGN is viewed with one of its relativistic jets in close proximity ($\leq 10^6$) to our line of sight, it is categorized as a blazar (Urry & Padovani 1995). Blazars club together BL Lacertae objects, which have nearly featureless optical continua and many flat spectrum radio quasiars, (FSRQs) that show extensive broad emission lines (e.g., Agarwal et al. 2015). Blazars are observed to be particularly violent AGNs, involving multiple outstanding attributes, including: dominance of non-thermal emission; high polarization; extreme flux variability across the entire electromagnetic (EM) spectrum; core-dominated radio morphology; and flat radio spectrum. All of these can be understood in terms of relativistic motion of plasma in the jets and Doppler boosting (e.g., Agarwal et al. 2016; Gaur et al. 2012a). The high polarization (> 3%) of their radio to optical emission means that the synchrotron emission mechanism is responsible for broadband non-thermal EM radiations from blazars at lower frequencies (radio through the UV or X-ray bands), while at higher frequencies it is likely to be dictated by inverse Compton (IC) scattering of seed photons by the same electrons producing the synchrotron emission. Blazar spectral energy distributions (SEDs) demonstrate a double-peak structure (e.g., Gaur et al. 2012a). The low energy peaked blazars (LBLs) have the first SED bump peak in mm to op-
tical bands and the second bump at GeV energies, while the high energy peaked blazars (HBLs) have the first component peak at UV/X-ray while the second range up to TeV energies (Finke & Becker 2014). The BL Lac/FSRQ subclasses also can be distinguished based on optical polarization properties: BL Lac objects show an amplified polarization towards the blue, probably arising due to some intrinsic phenomenon related to the jet-emitting region (Stocke et al. 1991; Marcha et al. 1996), while the FSRQs trend in the opposite direction, possibly because of significant contributions from the unpolarized quasi-thermal emission from the accretion disc and surrounding region.

Blazar observations often show detectable flux variations down to time periods of a few minutes to hours; these must arise from acute physical conditions within small, sub-parsec scale, regions (e.g., Gupta et al. 2016a). Blazar variability is conveniently sectioned into three classes, based on their observed time-scales: flux changes occurring over a time-scale of a day or less and up to a few hundredths of a magnitude is termed as intra-day variability (IDV) (Wagner & Witzel 1995), or microvariability (Miller et al. 1989), or intra-night variability (Gopal-Krishna et al. 1993); variations in flux, typically of a few tenths of a magnitude, that extend from days to weeks are known as short-term variability (STV); while variations ranging from several months to a few years are called long-term variability (LTV) (Gupta et al. 2004). Extensive studies of STV and LTV for blazars have often shown variations exceeding ~1 mag and some have spanned over ~5 mag. These flux variabilities in blazars could either be initiated through unstable accretion disc phenomena or solely through changes in the doppler-boosted emission of the relativistic jets (Ulrich et al. 1997).

Studies of variability timescales and amplitudes serve as key tools in understanding physical processes in the jets and the sizes and locations of the emission regions in AGN.

1.1 Mrk 421

Markarian 421 (B2 1101+38; Mrk 421 hereafter) is a nearby elliptical active galaxy ($\alpha_{2000} = 11h 04m 27.3139s$ and $\delta_{2000} = +38\degree 12\arcmin 31.7991\arcsec$) with an intense point-like nucleus, encompassing a $\sim 3.6 \times 10^8 M_\odot$ black hole (Wagner 2008). The nuclear source is classified as of the BL Lacertae type as it has a featureless optical spectrum, strongly polarized and variable optical and radio fluxes, and compact radio emission. Mrk 421 has a SED well characterised by a classic two peak shape (Urry & Padovani 1995; Ulrich et al. 1997). Most of these observed properties of Mrk 421 are understood to arise from a relativistic jet spotted at a small angle to our line of sight (Urry & Padovani 1995). Relativistic electrons radiating via the synchrotron process produce a non-thermal SED with a polarised continuum extending from the radio to the soft X-ray bands. Mrk 421 ($z = 0.031$) is one of the closest blazars, at a distance of 134 Mpc ($H_0 = 71$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.27, \Omega_\Lambda = 0.73$) and its synchrotron emission peak was long ago found to lie in the range of 0.1 keV to several keV (Punch et al. 1992). The Whipple Cherenkov Telescope claimed to have detected this extragalactic source at TeV energy range (0.5–1.5 TeV) (Schubnell et al. 1993) and it has been confirmed as a TeV source by multiple ground-based $\gamma$-ray telescopes (e.g., Abeysekara et al. 2017). The Compton Gamma-Ray Observatory (CGRO) easily observed Mrk 421 in the GeV band from space. Mrk 421 is the brightest extragalactic object in $\gamma$-rays in the northern hemisphere (e.g., Gaur et al. 2012a).

Thanks to its proximity, observational studies of Mrk 421 are pervasive throughout the entire EM spectrum. The source has had its radio emission followed over the span of 25 years at multiple frequencies (Hovatta et al. 2015, and references therein). It has shown rapid and extreme optical variability, including LTV of $\sim 4.6$ mag (Stein et al. 1976), and IDV up to $\sim 1.4$ mag of brightness change over a very short period ($\sim 2.5$ hours) (Guanzhong et al. 1988). Three decades of NIR data reported by Fan & Lin (1999) provide IDV and STV confirmation of its blazar nature. In 2006, the source was observed with a peak flux $\sim 85$ mCrab in the 2.0–10.0 keV band, indicating that the first peak of SED occurred at an energy beyond 10 keV (Tramacere et al. 2009; Ushio et al. 2009). There were reports of “orphan flares” (Fraija et al. 2015) in TeV $\gamma$-rays, (those not having corresponding increased X-ray emission), in Mrk 421 during 2003 and 2004 multi-wavelength campaigns. On June 10, 2008 Super-AGILE detected a hard X-ray flare. MAXI (Monitor of ALL-sky X-ray Image) marked the strongest X-ray flare in February 2010 ($\sim 164\pm17$ mCrab) (Isobe et al. 2015). HESS (High Energy Stereoscopic System) (Aharonian et al. 2005) and MAGIC (Major Atmospheric Gamma Imaging Cherenkov Telescopes) (Albert et al. 2007) observed the time-average high energy spectrum of Mrk 421 during its flaring stages.

The dominant synchrotron-self-Compton (SSC) model considers that the same electron population is responsible for the production of soft X-rays and high energy $\gamma$-rays. The SSC model agrees with the results of Blazejowski et al. (2005) and Horan et al. (2009), where the fluxes were well correlated with a time lag of less than 1.5 days (MAGIC Collaboration et al. 2016). In April 2013, Mrk 421 was observed to undergo a major X-ray outburst and was comprehensively investigated by multiple observational facilities, including the NuSTAR and $Swift$ satellites. Intensive studies of Mrk 421 probing its multi-wavelength (MW) behaviour are numerous (Takahashi et al. 1994; Kerrick et al. 1995; Gupta et al. 2004; Costa et al. 2008; Pitteri et al. 2008; Smith et al. 2008; Lico et al. 2012; Gaur et al. 2012b; Blasi et al. 2013; Pian et al. 2014; Paliya et al. 2015; Sinha et al. 2015; Hovatta et al. 2015; Baloković et al. 2016, and references therein). MW campaigns incorporating Fermi-LAT gamma-ray detections comprehensively studied Mrk 421 and produced its first ever complete $\gamma$-ray continuum during a quiescent state (Abdo et al. 2014). A multi-decade optical light curve spanning 1900 to 1991 was extracted by Liu et al. (1997) in the B-band, suggesting two possible observed time periods of 23.1±1.1 yrs and 15.3±0.7 yrs in those flux variations (Sinha et al. 2016). A significant amount of correlation ($\sim 68\%$) was found with X-ray data from RXTE-ASM, when Tluczykont & H.E.S.S. Collaboration (2010) studied the long term VHE light curve of the source. Strong episodes of TeV–Xray correlation were discussed by Katarzyński et al. (2005). The typical nature of moderate X-ray–GeV flux correlations has been recently examined by Bartoli et al. (2015) through multi-wavelength observations made from 2008 to 2013.
The least well understood aspect of blazar variability is probably seen on IDV timescales. To search for and analyze IDV in blazars, we are working on a project in which we study data taken with various ground and space based telescopes (Gupta et al. 2008a,b, 2012, 2016a, 2017; Gaur et al. 2010, 2012a,b,c, 2015a; Bachev et al. 2012; Agarwal & Gupta 2015; Agarwal et al. 2015, 2016; Kalita et al. 2015; Pandey et al. 2017). In this paper, we present a study of the IDV of Mrk 421 using the Chandra X-ray Observatory satellite. We employ all the archival data taken by Chandra since its launch, extending from 2000 May 29 to 2015 July 02 (∼16 years) and totaling 72 IDV light curves. This is the most extensive IDV study of Mrk 421 in the X-ray band, covering the longest temporal span. This work provides us with better understanding of the X-ray variability properties of Mrk 421, along with the correlations between hard and soft X-ray bands.

The paper is organized as follows. Section 2 briefly describes the Chandra satellite instrumentation along with the methodology for data reduction. Data analysis techniques used to search for flux and spectral variability are discussed in Section 3. Section 4 and Section 5 give our results and a discussion, respectively. Our conclusions are reported in Section 6.

2 CHANDRA X-RAY SATELLITE AND DATA REDUCTION

Launched on July 23, 1999 as a part of the “Great Observatories”, this NASA telescope has been a phenomenal tool to study high energy sources such as compact binaries, quasars and supernovas. Chandra’s High Resolution Mirror Assembly (HRMA) typically produces images with a half-power diameter (HPD) of the point spread function (PSF) of <0.5 arcsec. The High Energy Transmission Grating (HETG) and the Low Energy Transmission Grating (LETG) have high resolving powers when compared to their bandwidths and together cover the energy range from 0.1 to 10 keV. ACIS (Advanced CCD Imaging Spectrometer) and HRC (High Resolution Camera) are the in-house focal instruments of the Science Instrument Module (SIM) (e.g., Weissskopf et al. 2000).

ACIS consists of two CCD arrays: four arrangements of 2×2 arrays, known as ACIS-I (having front-illuminated (FI) CCDs) and six arrangements of 1×6 arrays, ACIS-S (consisting of 4 FI and 2 back-illuminated (BI) CCDs). The time resolution of two ACIS detectors is 3.2 sec (e.g., Weissskopf et al. 2000). When observing a wide-field (16′×16′) and/or requiring high energy response, ACIS-I is preferred while imaging observations having a low energy response and a smaller field-of-view (8′×8′) are provided by ACIS-S.

The micro channel plate instrument, HRC, has the fastest time resolution of 16 µsec. It employs two detectors, one of which, HRC-I is calibrated for imaging with a wide field-of-view (FoV) of ∼30′×30′. The other, HRC-S, is primarily used with the LETG and has a long FoV of ∼7′×97′ (e.g., Weissskopf et al. 2000).

2.1 Data Reduction

Mrk 421 was observed by Chandra between 2000 May 29 to 2015 July 02, providing a rich set of data for the study of its variable nature in the X-ray energy range of 0.3-10 keV. We downloaded 72 observation IDs from the HEASARC Data Archive1. The list of Observation IDs, dates, start times, detectors used, gratings and exposure times are given in Table 1. The majority of these observations were used for calibration or spectroscopic study of the warm-hot intergalactic medium filaments in the direction of the blazar (e.g., Nicastro et al. 2005; Kaastra et al. 2006; Rasmussen et al. 2007; Yao et al. 2008). Hence the extensive timing analysis we present here is unique for Chandra data.

The Chandra Interactive Analysis of Observations (CIAO2 version 4.9) package was used in conjunction with CALDB version 4.7.7 to process the data. We first reprocessed the level 2 event file to apply the updated calibration data using the CIAO script chandra_repro. We then applied a barycenter correction to the reprocessed level 2 event file using the CIAO tool azbary. Out of 72 observations, 48 were done with the ACIS detector and remaining 24 with HRC. Although gratings are used in all these observations, there is a possibility of pile-up in the undispersed (zeroth order) events for a bright source such as Mrk 421 in observations performed with the ACIS detector. The dispersed (first order) events are, however, free from pile-up. So, for the 48 observations taken with ACIS, we determined fluxes from a rectangular region of 800″×200″ that contains only the dispersed source photons. For observations made with HRC we took a circular region of radius 10″ centered on the source to extract light curves. We have also taken into account the Dead Time Factor (DTF3) while creating the HRC light curves. Finally the 0.3-10.0 keV light curves were extracted using the CIAO tool dmextract with a binning of 500 secs. Due to the brightness of Mrk 421, the background contribution is negligible.

3 ANALYSIS TECHNIQUES

3.1 Excess Variance

Although AGNs in general, and blazars in particular, are generally characterized by rapid X-ray variability, when observed there will be some innate experimental noise. Measurement errors in the LC produce finite uncertainties, σerr,i, for each of the i measurements that contribute additional variance to the observed variance (e.g., Pandey et al. 2017). The quantitative measure of the true variance is known as excess variance and yields the magnitude of variability. Thus the excess variance is defined for an observed LC having N measured flux values xi as (Vaughan et al. 2003)

\[
\sigma^2_{XS} = S^2 - \sigma^2_{err}
\]  (1)

1. https://heasarc.gsfc.nasa.gov/db-perl/W3Browse/w3browse.pl
2. http://cxc.harvard.edu/ciao/
3. The DTF characterizes the detector’s deviation from the standard detection efficiency.
Table 1. Observation log of Chandra data for Mrk 421.

| ObsID | Date of Observation (dd-mm-yyyy) | Start Time (UT) (hh:mm:ss) | Detector | Grating | Exposure Time (ks) |
|-------|----------------------------------|-----------------------------|----------|---------|-------------------|
| 1714  | 29-05-2000                       | 11:39:48                    | ACIS-S   | HETG    | 19.83             |
| 1715  | 29-05-2000                       | 17:40:11                    | HRC-S    | LETG    | 19.84             |
| 4148  | 06-05-2004                       | 14:19:35                    | HRC-S    | LETG    | 99.98             |
| 5318  | 06-05-2004                       | 14:53:40                    | ACIS-S   | LETG    | 30.16             |
| 5171  | 13-07-2004                       | 17:19:41                    | ACIS-S   | LETG    | 67.15             |
| 8378  | 07-01-2007                       | 00:05:02                    | ACIS-S   | LETG    | 9.84              |
| 8396  | 07-01-2007                       | 03:08:15                    | ACIS-S   | LETG    | 29.16             |
| 10671 | 10-10-2009                       | 14:53:40                    | ACIS-S   | LETG    | 30.16             |
| 10664 | 10-10-2009                       | 14:53:40                    | ACIS-S   | LETG    | 30.16             |
| 10665 | 10-10-2009                       | 14:53:40                    | ACIS-S   | LETG    | 30.16             |
| 10666 | 10-10-2009                       | 14:53:40                    | ACIS-S   | LETG    | 30.16             |
| 10667 | 10-10-2009                       | 14:53:40                    | ACIS-S   | LETG    | 30.16             |
| 10668 | 10-10-2009                       | 14:53:40                    | ACIS-S   | LETG    | 30.16             |
| 10669 | 10-10-2009                       | 14:53:40                    | ACIS-S   | LETG    | 30.16             |
| 10670 | 10-10-2009                       | 14:53:40                    | ACIS-S   | LETG    | 30.16             |
| 10671 | 10-10-2009                       | 14:53:40                    | ACIS-S   | LETG    | 30.16             |

where $S^2$ is the total variance of the LC, and is given by

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

and $\sigma_{err}^2$ is the mean square error is given by

$$\sigma_{err}^2 = \frac{1}{N} \sum_{i=1}^{N} \sigma_{err,i}^2,$$

where $\bar{x}$ is the arithmetic mean of $x_i$.

It makes sense to normalise the excess variance

$$\sigma_{XS}^2 = \sigma_{XS}^2/\bar{x}^2,$$

and the fractional rms variability amplitude, $F_{var}$, is defined as

$$F_{var} = \sqrt{\frac{S^2 - \sigma_{err}^2}{\bar{x}^2}}.$$  \hfill (5)

It can be shown that the uncertainty in $F_{var}$ is given by (e.g., Vaughan et al. 2003),

$$\text{err}(F_{var}) = \sqrt{\left( \frac{1}{N} \frac{\sigma_{err}^2}{2\bar{x}^2F_{var}} \right)^2 + \left( \frac{\sigma_{err}^2}{N} \frac{1}{\bar{x}} \right)^2}.$$ \hfill (6)

3.2 Discrete Correlation Functions

The Discrete Correlation Function (DCF) technique was first introduced to astronomical time series by Edelson & Krolik (1988) and later modified to give better error estimates by Hufnagel & Bregman (1992). The DCF

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can be used to find possible time-lags between bands and so correlate multi-frequency AGN LCs data, even when they are distributed irregularly over time, as is typical. Two discrete data trains $x$ and $y$ are taken into account to collect unbinned correlations (UDCF) (e.g., Pandey et al. 2017) via

$$F_{ij} = \frac{(x_i - \bar{x})(y_j - \bar{y})}{\sqrt{\sigma_x^2 \sigma_y^2}},$$

for the data sets $x_i$ and $y_j$ having $\bar{x}$ and $\bar{y}$ as their mean values, and $\sigma_x$ and $\sigma_y$ as their standard deviations, respectively (Gaur et al. 2015b).

In order to obtain a normalized DCF, one must bin the calculated UDCF, but the selected bin size should neither be too large to lose any important data points, nor too small so as to produce spurious correlations. The DCF then can be computed by taking the average of a number, $M$, of UDCF values for each time delay $\Delta t_{ij} = t_j - t_i$ that lie in the range $\tau - \Delta \tau / 2 \leq \Delta t_{ij} < \tau + \Delta \tau / 2$ as,

$$DCF(\tau) = \frac{1}{M} \sum F_{ij},$$

with $\tau$ being the center of the time bin $\Delta \tau$. Each bin has a standard error estimate that is given as (Edelson & Krolik 1988),

$$\sigma_{DCF}(\tau) = \sqrt{\frac{\sum (F_{ij} - DCF(\tau))^2}{M - 1}}.$$

The Auto Correlation Function (ACF) is the special case of the DCF where a data train is correlated with itself ($x = y$), automatically generating a peak at $\tau = 0$. This peak points out the absence of any time lag, and any periodicity in

\[\text{Table 1. continued.}\]

| ObsID | Date of Observation (dd-mm-yyyy) | Start Time (UT) (hh:mm:ss) | Detector | Grating | Exposure Time (ks) |
|-------|----------------------------------|-----------------------------|----------|---------|-------------------|
| 13104 | 04-07-2011 22:07:18              | HRC-S                       | LETG     |         | 10.18             |
| 13105 | 05-07-2011 01:06:06              | ACIS-S                      | HETG     |         | 15.00             |
| 14266 | 07-04-2012 20:29:18              | ACIS-S                      | LETG     |         | 30.05             |
| 14320 | 03-07-2012 11:34:05              | ACIS-S                      | HETG     |         | 15.03             |
| 14322 | 03-07-2012 16:07:49              | HRC-S                       | LETG     |         | 10.01             |
| 14396 | 03-07-2012 19:00:24              | HRC-S                       | LETG     |         | 9.79              |
| 14321 | 03-07-2012 22:06:42              | ACIS-S                      | LETG     |         | 10.05             |
| 14323 | 04-07-2012 01:13:05              | HRC-S                       | LETG     |         | 10.18             |
| 14324 | 04-07-2012 04:09:45              | HRC-S                       | LETG     |         | 9.79              |
| 14325 | 04-07-2012 07:07:03              | ACIS-S                      | LETG     |         | 10.05             |
| 14326 | 04-07-2012 10:13:26              | HRC-S                       | LETG     |         | 10.19             |
| 14327 | 04-07-2012 16:07:26              | ACIS-S                      | HETG     |         | 15.04             |
| 15607 | 07-02-2013 19:15:19              | ACIS-S                      | LETG     |         | 30.07             |
| 15476 | 03-04-2013 00:36:24              | ACIS-S                      | LETG     |         | 30.05             |
| 15477 | 30-06-2013 16:15:37              | ACIS-S                      | HETG     |         | 14.65             |
| 15478 | 30-06-2013 20:46:21              | ACIS-S                      | LETG     |         | 10.06             |
| 15479 | 30-06-2013 23:58:37              | HRC-S                       | LETG     |         | 10.14             |
| 15480 | 01-07-2013 02:57:24              | ACIS-S                      | LETG     |         | 9.76              |
| 15481 | 01-07-2013 05:56:13              | HRC-S                       | LETG     |         | 10.19             |
| 15482 | 01-07-2013 08:55:01              | ACIS-S                      | LETG     |         | 9.77              |
| 15483 | 01-07-2013 11:53:49              | HRC-S                       | LETG     |         | 10.19             |
| 15484 | 01-07-2013 14:52:38              | ACIS-S                      | HETG     |         | 14.50             |
| 16474 | 06-03-2014 08:13:12              | ACIS-S                      | LETG     |         | 60.07             |
| 16424 | 25-06-2014 13:54:38              | HRC-S                       | LETG     |         | 15.05             |
| 16425 | 25-06-2014 20:44:18              | ACIS-S                      | LETG     |         | 10.08             |
| 16426 | 25-06-2014 23:56:09              | HRC-S                       | LETG     |         | 10.15             |
| 16427 | 26-06-2014 02:55:01              | ACIS-S                      | LETG     |         | 10.08             |
| 16428 | 26-06-2014 06:01:20              | HRC-S                       | LETG     |         | 10.18             |
| 16429 | 26-06-2014 09:00:09              | ACIS-S                      | LETG     |         | 10.08             |
| 16430 | 26-06-2014 12:06:31              | HRC-S                       | LETG     |         | 10.17             |
| 16431 | 26-06-2014 15:05:17              | ACIS-S                      | HETG     |         | 15.05             |
| 17385 | 01-07-2015 00:42:11              | ACIS-S                      | HETG     |         | 15.03             |
| 17387 | 01-07-2015 20:54:30              | HRC-S                       | LETG     |         | 10.18             |
| 17389 | 01-07-2015 23:51:09              | HRC-S                       | LETG     |         | 10.19             |
| 17391 | 02-07-2015 02:46:19              | HRC-S                       | LETG     |         | 10.18             |
| 17392 | 02-07-2015 05:43:39              | ACIS-S                      | HETG     |         | 14.06             |
the data would be marked by the presence of other strong peaks (Agarwal & Gupta 2015). Generally, two correlated data signals have a DCF value > 0, while a DCF value < 0 indicates that the two data sets are anti-correlated, and a DCF value = 0 means that the two data trains have no correlation (Gaur et al. 2014).

3.3 Hardness Ratio

The Hardness Ratio (HR) is an effective and elementary model-independent method which can simply characterise spectral variations, and is defined as

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

where, \( H \) is the net count rate in the hard energy band and \( S \) is the net count rate in the soft energy band (e.g., Pons et al. 2016). In order to examine spectral variability in our X-ray light curves, we split the LCs into a soft X-ray energy band (0.3-2.0 keV) and a hard X-ray energy band (2.0-10.0 keV) and plotted HR variations with time.

3.4 Duty Cycle

Calculating the duty cycle (DC) gives us a direct estimation of the time fraction for which the object was variable. We determined the DC for Mrk 421 using the definition of Romero et al. (1999), which was thereafter adopted by many authors (e.g., Agarwal et al. 2016). LCs with moni-

| ObsID  | Soft(0.3-2 keV) | Hard(2-10 keV) | Total(0.3-10 keV) | ACF (ks) | Bin-size (ks) |
|--------|----------------|----------------|-------------------|----------|---------------|
| 1714   | 15.24 ± 0.54   | 18.96 ± 0.54   | 16.79 ± 0.37      | --       | 1.00          |
| 1715*  | --             | --             | 2.62 ± 0.30       | --       | 1.00          |
| 4148   | 10.49 ± 0.06   | 16.27 ± 0.09   | 12.27 ± 0.05      | 30.50    | 3.00          |
| 4149*  | --             | --             | 18.56 ± 0.07      | --       | 5.00          |
| 5318   | 9.51 ± 0.12    | 14.62 ± 0.16   | 11.02 ± 0.09      | 19.50    | 1.50          |
| 5171   | 6.02 ± 0.12    | 9.73 ± 0.19    | 7.03 ± 0.10       | --       | 5.00          |
| 5332   | 4.35 ± 0.12    | 8.67 ± 0.21    | 5.12 ± 0.10       | --       | 3.00          |
| 8378   | 3.77 ± 0.24    | 4.46 ± 0.49    | 3.95 ± 0.21       | --       | 2.00          |
| 6925   | 2.15 ± 0.27    | 4.43 ± 0.49    | 2.80 ± 0.24       | 10.07    | 1.00          |
| 8396*  | --             | --             | 7.22 ± 0.16       | --       | 2.00          |
| 10671  | 3.94 ± 0.17    | 5.14 ± 0.26    | 4.32 ± 0.14       | 14.98    | 1.00          |
| 10664  | 2.54 ± 0.18    | 2.39 ± 0.31    | 2.21 ± 0.16       | --       | 1.00          |
| 11606  | 6.67 ± 0.56    | 2.07 ± 0.32    | 0.86 ± 0.47       | --       | 0.60          |
| 11606  | 1.11 ± 0.40    | 0.23 ± 2.66    | 0.65 ± 0.47       | --       | 0.60          |
| 11607  | 1.04 ± 0.45    | 3.14 ± 0.62    | 1.41 ± 0.33       | --       | 0.70          |
| 11960  | 7.27 ± 0.36    | 10.56 ± 0.53   | 8.21 ± 0.29       | --       | 2.00          |
| 11961  | 7.45 ± 0.26    | 10.55 ± 0.31   | 8.26 ± 0.19       | --       | 2.00          |
| 11962  | 4.16 ± 0.28    | 5.77 ± 0.39    | 4.66 ± 0.22       | 10.07    | 1.00          |
| 11963  | 4.08 ± 0.24    | 4.03 ± 0.30    | 3.65 ± 0.20       | --       | 2.00          |
| 11964  | 1.32 ± 0.37    | 3.97 ± 0.34    | 3.13 ± 0.22       | --       | 2.00          |
| 11967  | 5.80 ± 0.38    | 8.11 ± 0.52    | 8.55 ± 0.30       | --       | 2.00          |
| 10663  | 2.33 ± 0.36    | 4.36 ± 0.30    | 3.60 ± 0.23       | --       | 0.60          |
| 11970  | 2.11 ± 0.28    | 4.52 ± 0.43    | 2.48 ± 0.20       | --       | 1.00          |
| 10665* | --             | --             | 0.59 ± 0.40       | --       | 0.60          |
| 12121  | 7.13 ± 0.23    | 13.42 ± 0.37   | 8.43 ± 0.21       | --       | 1.00          |
| 10667* | --             | --             | 5.71 ± 0.22       | --       | 1.00          |
| 10668  | 7.84 ± 0.20    | 10.72 ± 0.29   | 8.45 ± 0.17       | --       | 1.00          |
| 10669* | --             | --             | 2.59 ± 0.25       | --       | 1.00          |
| 11966  | 18.70 ± 0.15   | 27.95 ± 0.22   | 21.31 ± 0.12      | --       | 3.00          |
| 10670  | 2.52 ± 0.55    | 4.37 ± 0.50    | 3.66 ± 0.35       | --       | 1.00          |
| 12122* | --             | --             | 2.54 ± 0.54       | --       | 2.00          |
| 13097  | 6.42 ± 1.09    | 7.93 ± 2.47    | 6.28 ± 0.95       | --       | 2.00          |
| 13098  | 5.13 ± 0.75    | 4.14 ± 0.81    | 4.78 ± 0.56       | --       | 1.00          |
| 13099  | 2.48 ± 0.51    | 2.72 ± 1.00    | 1.65 ± 0.45       | --       | 1.00          |
| 13100* | --             | --             | 2.07 ± 0.49       | --       | 1.00          |

* Observation done with HRC detector in which the light curve can not be split into different energy bands, hence the values of \( F_{\text{var}} \) are not quoted for Soft and Hard energy bands.
Table 2. continued.

| ObsID | Soft(0.3-2 keV) | F_{\text{var}} (percent) | Hard(2-10 keV) | Total(0.3-10 keV) | ACF (ks) | Bin-Size (ks) |
|-------|-----------------|---------------------------|-----------------|-------------------|---------|-------------|
| 13104* | –               | –                         | –               | 1.69 ± 0.48       | –       | 1.00        |
| 13105  | 4.21 ± 0.68     | 6.21 ± 0.65               | –               | 4.56 ± 0.46       | –       | 2.00        |
| 14266  | 3.28 ± 0.41     | 4.93 ± 0.73               | –               | 3.33 ± 0.35       | 5.51    | 1.00        |
| 14320  | 3.57 ± 0.95     | 6.11 ± 0.99               | –               | 4.33 ± 0.66       | –       | 1.00        |
| 14322* | –               | –                         | –               | 2.68 ± 0.43       | –       | 1.00        |
| 14396* | –               | –                         | –               | 0.86 ± 0.64       | –       | 1.00        |
| 14321  | 1.45 ± 0.59     | 2.33 ± 1.25               | –               | 1.06 ± 0.62       | –       | 1.00        |
| 14323* | –               | –                         | –               | 2.52 ± 0.42       | –       | 1.00        |
| 14324* | –               | –                         | –               | 2.53 ± 0.40       | –       | 1.00        |
| 14325  | 1.21 ± 0.62     | 1.04 ± 2.11               | –               | 0.84 ± 0.69       | –       | 1.00        |
| 14326* | –               | –                         | –               | 8.98 ± 0.34       | –       | 1.00        |
| 14397* | –               | –                         | –               | 1.19 ± 0.44       | –       | 1.00        |
| 14327  | 5.11 ± 0.60     | 7.86 ± 0.62               | –               | 6.16 ± 0.44       | –       | 1.00        |
| 15607  | 6.87 ± 0.19     | 10.98 ± 0.31              | –               | 7.65 ± 0.15       | 9.51    | 1.00        |
| 15476  | 10.05 ± 0.16    | 16.73 ± 0.23              | –               | 12.03 ± 0.13      | –       | 1.00        |
| 15477  | 5.44 ± 0.42     | 8.60 ± 0.40               | –               | 7.09 ± 0.28       | –       | 1.00        |
| 15478  | 7.63 ± 0.30     | 10.60 ± 0.49              | –               | 8.45 ± 0.22       | –       | 1.00        |
| 15479* | –               | –                         | –               | 4.52 ± 0.26       | –       | 1.00        |
| 15480  | 1.87 ± 0.33     | 2.86 ± 0.61               | –               | 2.00 ± 0.29       | –       | 1.00        |
| 15481* | –               | –                         | –               | 2.52 ± 0.29       | –       | 1.00        |
| 15482  | 0.51 ± 0.61     | 1.40 ± 0.79               | –               | 0.74 ± 0.43       | –       | 1.00        |
| 15483* | –               | –                         | –               | 5.07 ± 0.28       | –       | 1.00        |
| 15484  | 3.41 ± 0.49     | 5.44 ± 0.46               | –               | 4.58 ± 0.31       | –       | 1.00        |
| 16474  | 9.59 ± 0.09     | 12.12 ± 0.13              | –               | 10.38 ± 0.07      | –       | 5.00        |
| 16424  | 7.77 ± 0.70     | 12.88 ± 0.69              | –               | 10.67 ± 0.48      | –       | 1.00        |
| 16425  | 3.29 ± 0.50     | 3.70 ± 0.91               | –               | 3.10 ± 0.41       | –       | 1.00        |
| 16426* | –               | –                         | –               | 3.82 ± 0.40       | –       | 1.00        |
| 16427  | 2.09 ± 0.47     | 1.19 ± 1.30               | –               | 2.00 ± 0.43       | –       | 1.00        |
| 16428* | –               | –                         | –               | 3.39 ± 0.41       | –       | 1.00        |
| 16429  | 6.65 ± 0.44     | 9.31 ± 0.74               | –               | 6.79 ± 0.39       | –       | 1.00        |
| 16430* | –               | –                         | –               | 4.76 ± 0.41       | –       | 1.00        |
| 16431  | 1.59 ± 1.11     | 1.67 ± 1.06               | –               | 2.33 ± 0.58       | –       | 1.00        |
| 17385  | 7.03 ± 0.75     | 7.25 ± 0.73               | –               | 7.43 ± 0.52       | –       | 1.00        |
| 17387* | –               | –                         | –               | 3.52 ± 0.34       | –       | 1.00        |
| 17389* | –               | –                         | –               | 6.18 ± 0.29       | –       | 1.00        |
| 17391* | –               | –                         | –               | 2.43 ± 0.30       | –       | 1.00        |
| 17392  | 4.78 ± 0.55     | 7.57 ± 0.52               | –               | 6.15 ± 0.37       | –       | 1.00        |

* Observation done with HRC detector in which the light curve cannot be split into different energy bands, hence the values of F_{\text{var}} are not quoted for Soft and Hard energy bands.

4 RESULTS

We have analysed 72 Chandra observations of Mrk 421 that provide good data, as tabulated in Table 1. The resulting X-ray LCs are shown in Fig. 1. We have searched for IDV in these LCs and visual inspection of them frequently show the presence of clear variability (Kalita et al. 2017). We have computed IDV variability parameters in Table 2, which include excess variance, fractional variance (F_{\text{var}}) and any timescales indicated by the ACFs. It is evident that the F_{\text{var}} amplitudes of most of the individual observations are considerable, with values exceeding 3 times the error for the total counts for 65 out of the 72 observations (Paliya et al. 2015; Baloković et al. 2016). Observation ID 11966, taken on 2010
March 14, shows the highest value of variability amplitude (21.31 ± 0.12 per cent) over the entire period, and was observed for 30 ks. Whenever possible (for ACIS data only), we split the X-ray light curves into two energy bands: the soft X-ray energy band spans 0.3–2.0 keV while the hard band is taken as 2.0–10.0 keV. The fractional variances separately calculated for hard and soft bands are also given in Table 2; this data provides evidence for the hard band being more variable than the soft band (for 41 out of 48 observations). Statistically valid variations from Mrk 421 are clearly indicated by $F_{\text{var}}$ computations. These allowed us to compute the DC of our source to be $\sim 84\%$, showing a strong presence of X-ray IDV.

Fig. 2 displays the LCs of the soft and hard energy
bands, both of which are shown in the left panels, with HR plots in the middle panels and DCF results between the hard and soft LCs displayed in the right panels. The hardness ratios plotted against time show clear indications of spectral variations. The DCF plots quantify the strong positive correlation between the hard and soft bands, at least whenever considerable variability is present. We fitted each DCF plot with a Gaussian function \( y = A \exp\left(-(x - x_0)^2/w\right) \), with amplitude \( A \), central value \( x_0 \), and width, \( w \) to estimate any possible time lag, and found a time lag almost equal to zero in each case. These results suggest that both soft and hard bands are emitted from the same region at the same time (e.g., Pandey et al. 2017).

The Auto-Correlation Function plots are displayed in Fig. 3, and they provide strong evidence of variability timescales for seven observation IDs. The timescales are taken from the locations of significant non-zero peaks in the ACF. For seven plots such timescales range from 5.5 to 30.5 ks and are presented in Table 2. The remaining ACF plots either exhibit such a high noise level that any variability timescales cannot be ascertained or simply do not indicate the presence of any variability (Gupta et al. 2016b).

The course of this entire set of Chandra observations of Mrk 421 spans over 16 years. The LTV LC of the mean of the total X-ray fluxes is shown in Fig. 4. Very substantial variations, ranging up to 21.31 ± 0.12 per cent, are seen in the individual observational count rates. The LTV count rates vary from 0.396±0.004 to 48.226±0.023, clearly emphasizing how variable this blazar is. No clear patterns can be discerned from a visual inspection of these LTV data.

In Fig. 5 we show plots of the HR against flux. This spectral index-flux representation was studied to uncover patterns in the HR as a function of 0.3–10.0 keV count rates for different time intervals. Spectral evolution of Mrk 421 during this ≈16 yrs of observation is clearly marked by changing relative strength of particle acceleration and synchrotron cooling processes in X-ray emitting regions (Kalita et al. 2015). The presence of clockwise or anti-clockwise loops in this spectral hardness-flux plots reveals information about the leading emission mechanism during that particular period. For these HR against count rate plots, we considered the entire set of 48 observations made with ACIS for which the HR can be measured and if we detected any loop in the plot we considered that segment as one epoch and started a search for subsequent loops. This way, we found eight distinct epochs having either clockwise or anti-clockwise loops that include a substantial majority of the observations (31 of 48). X-ray emissions can be understood as arising from high energy relativistic particles that are accelerated as a result of shocks propagating in the relativistic jets. When these accelerated particles come in contact with the inhomogeneous magnetic fields significant synchrotron emission extends into the X-ray band, which will dominate the cooling process. Fig. 5 contains an anti-clockwise loop for Epoch 1 which can be understood as a hard-lag (Zhang et al. 2002). This leads us to conclude that particles were being accelerated to very high speeds during that time span (Kalita et al. 2015). Dominance of particle acceleration mechanisms were again indicated in Epoch 3. Epochs 4 and 7 also have anti-clockwise loops, providing evidence for particles being accelerated in the internal shocks as they outflow along the jets. Clockwise loops, or soft-lags, were displayed by Epochs 2 and 5 and then again by Epochs 6 and 8. This implies that the synchrotron cooling mechanism dominated the X-ray emission in those particular periods.

5 DISCUSSION

An important route to understanding the emission mechanisms in blazars and other AGN involves careful measurement of strong flux variations on diverse timescales. Studies of rapid variability of blazars have also helped us to determine the key properties of the emitting region such as its size, location and structure (e.g., Ciprini et al. 2003; Stein et al. 1976; Gupta et al. 2016b). Whenever extreme variability is combined with relatively weak spectral features, as in BL Lac objects, it has long been accepted that a relativistic jet close to the line of sight (LOS) is emitting the continuum; this results in the dramatic increase in the brightness of the observed radiation and a reduction of the observed variability timescales due to Doppler boosting (Blandford & Rees 1980; Ulrich et al. 1997). The high X-ray variations displayed by many blazars could arise either directly from the synchrotron emission or through Compton scattering of the lower-energy synchrotron photons (SSC) process, again supporting the idea of relativistic bulk motion in blazars (Hoyle & Burbidge 1966; Bassani & Dean 1983). In general, intrinsic AGN emission and variability can occur through two fundamental theoretical branches, either the purely relativistic-jet-based models (Marscher & Gear 1985; Gopal-Krishna & Wiita 1992; Marscher 2014; Calafut & Wiita 2015) or the accretion-disc based models (Mangalam & Wiita 1993; Chakrabarti & Wiita 1999). IDV and STV in radio-quiet quasars, and perhaps in certain blazars, if they are in very low states, can possibly be explained through instabilities
present in accretion discs (Mangalam & Wiita 1993). Yet any such accretion-disc based model does not provide a satisfactory explanation for the very strong and rapid variability on most timescales that can be much more easily provided by the doppler boosted radiations from relativistic jets (Chakrabarti & Wiita 1993).

An adiabatic shock-in-jet model can nicely explain blazar variability on LTV timescales (Marscher & Gear 1985; Wagner & Witzel 1995). The model describes relativistic shocks as arising from disturbances created in the inner portion of the jet that can quickly steepen into shocks. As they propagate through the jet, these shocks create major flux. Additional fluctuations are observed when these shocks interact with helical jet structures, by changing the effective viewing angle and hence Doppler factor (Gopal-Krishna & Wiita 1992; Camenzind & Kroegelenger 1992; Pandey et al. 2017). Relativistic jets also suffer some turbulence behind some of the shock regions, which can be held responsible for smaller STV and IDV (Marscher 2014; Calafut & Wiita 2015; Pollack et al. 2016).

Some blazars, such as Mrk 421, exhibit flaring TeV emissions on the timescales of a few minutes, which can be short when compared to the light crossing time of the SMBH of those blazars. Also, for TeV seed photons to escape from their source region, which is quite compact, it appears that the Lorentz factor of the emitting region needs to be $\gtrsim 50$. This is required in order to avoid absorption via pair production through interaction with soft radiation fields, but such extreme Lorentz factors are hard to achieve with a jet with a uniform bulk flow. The flaring states of Mrk 421 might be more naturally explained via a "jets-in-a-jet" model proposed by Giannios et al. (2009). This scenario can explain the origin of TeV emission along with fast X-ray variability through production of rapid flares arising from to the ultra-relativistic outflow of material from magnetic reconnection sites. The presence of multiple reconnection regions and the phenomena related to the rupturing of a large reconnection site make this model more flexible, so that the production of more slowly varying flares is also possible. Electrons accelerated within the jets would be responsible for rapid hard X-ray variability and the successive flares detected in Mrk 421. This phenomena can also yield the observed spectral hardening at high energies.

Certain parameters can be estimated, rather independently of model details, by assuming that synchrotron emission is responsible for the X-ray emission from HBLs, such as Mrk 421. In the observer’s frame, the acceleration timescale of the diffuse shock acceleration mechanism (Blandford & Eichler 1987) assumed to be the way in which electrons are accelerated, is given as (Zhang et al. 2002)

$$t_{\text{acc}}(\gamma) \simeq 3.79 \times 10^{-2} \left(\frac{1 + z}{\delta}\right) B^{-1} \gamma^{-1} \text{s}, \quad \text{(12)}$$

where, $\xi$ is defined as the acceleration parameter, $B$ is the magnetic field and $\gamma$ is the Lorentz factor of the electrons. Synchrotron emission is also believed to be the origin of the X-ray emission, when TeV blazars are considered. An individual electron with energy $E = \gamma m_e c^2$ has a synchrotron cooling timescale of,

$$t_{\text{cool}}(\gamma) \simeq 7.74 \times 10^{8} \left(\frac{1 + z}{\delta}\right) B^{-2} \gamma^{-1} \text{s}, \quad \text{(13)}$$

For the Chandra energy range, the critical synchrotron emission frequency $\nu \simeq 4.2 \times 10^{15} \frac{1 + z}{\delta} B^{-3} \gamma^{-1} \text{Hz}$. Although the minimum variability timescale found in this work is 5.5 ks, the variability associated with that observation is only $\sim 3\%$ so we took 9.51 ks as the shortest clear variability timescale, as $F_{\text{var}}$ exceeds $7\%$ for it. The cooling timescale should be greater than or equal to the minimum variability timescale or $\sim 9.51$ ks for Mrk 421 in this work. This implies,

$$B \geq 0.30(1 + z)^{1/3} \delta^{-1/3} \nu_{18}^{-1/3} \text{G}. \quad \text{(14)}$$

Although a range of values for $\delta$ for Mrk 421 between 20 and 50 (e.g., Tavecchio et al. 1998; Abdo et al. 2011; Zhu et al. 2016, and references therein) appear in the literature, we choose $\delta = 25$ (e.g., Baloković et al. 2016), and get,

$$B \geq 0.10 \nu_{18}^{-1/3} \text{G}. \quad \text{(15)}$$

Combining these values of $B$ and $\delta$, we estimate the electron Lorentz factor as,

$$\gamma \geq 3.06 \times 10^2 \nu_{18}^{3/2}. \quad \text{(16)}$$

The characteristic radius of emitting region can also be evaluated using the bound

$$R \leq \frac{c t_{\text{var}}}{1 + z} \leq 6.92 \times 10^{15} \text{cm.} \quad \text{(17)}$$

Relativistic electrons directly responsible for hard, variable X-ray emission, as are investigated by Chandra, must be repeatedly accelerated because of the short cooling timescales of these very high-energy electrons (Pandey et al. 2017). These electrons must be injected via one or more of the various possible acceleration mechanisms mentioned above. We note that diffusive-shock acceleration could be responsible both for variations in the flux and spectral hardening at high energies.

For this HBL we probed the X-ray spectral variability by analyzing the HR, as it serves as an easy and efficient way to understand changes in the spectra; however, the physical parameters that are responsible for spectral variability are not directly evaluated by this method. We observed that for Mrk 421 the HR increases as the flux (count rate) increases, or, as the flux is increasing, the spectrum tends to get flatter. Thus it seems that this source is following the general trend of “hardens-when-brighter” of the HSP type blazar as discussed previously (Plan et al. 1998; Zhang et al. 2002; Brinkmann et al. 2003; Ravasio et al. 2004; Pandey et al. 2017). The spectral hardness–flux analysis we conducted provides a model independent approach to understanding the spectral variations of the source. The presence of anti-clockwise loops in the plots indicates that the soft band leads the hard band (or there is a hard-lag between the two emissions), i.e., with the increase in the total flux of the source, the hard flux usually increases more than the soft flux. This indicates that the particle acceleration mechanism is predominantly responsible for the observed X-ray emission during that particular period of time (Bhagwan et al. 2016). When any clockwise loop (or soft-lag) occurs in the HR against flux plot, the soft flux increases more than the hard flux with increasing total flux. In these epochs, the hard band leads the soft band, as is the case when the synchrotron emission mechanism temporarily dominates the acceleration mechanism.
Figure 5. Spectral variations of Mrk 421 in various epochs with start and end points marking the loop directions. Each epoch corresponds to the time interval during which the data were acquired for each loop, considered from Epoch 1 to Epoch 8: Epoch 1: 29-05-2000 to 13-07-2004; Epoch 2: 08-11-2009 to 02-02-2010; Epoch 3: 04-02-2010 to 06-02-2010; Epoch 4: 13-03-2010 to 14-03-2010; Epoch 5: 14-03-2010 to 04-07-2011; Epoch 6: 05-07-2011 to 03-07-2012; Epoch 7: 07-02-2013 to 30-06-2013; and Epoch 8: 01-07-2013 to 25-06-2014.

6 CONCLUSIONS

We studied 72 Chandra light curves of the TeV blazar Mrk 421, and searched for variability timescales of IDV. The rapid X-ray variability studied here most likely originates within compact regions of the relativistic jet. Our conclusions are summarised as follows:

(i) The fractional variability amplitude provides a clear indication of variability on many occasions, with highest variability amplitude being over 21 per cent. The variability in hard energy X-ray bands presumably originates from a compact region within a relativistic jet.

(ii) The duty cycle for these variations is at least \( \approx 84 \) per cent which indicates that the source was exceptionally variable in the observed 16 year span.

(iii) We found evidence for timescales ranging from 5.5 to 30.5 ksec in 7 LCs of Mrk 421 using the ACF technique. Other observations have noisier ACF plots in which variability timescales are not clearly present. Using the shortest strong variability timescale of 9.51 ks, we can estimate key parameters in a fashion this is essentially independent of the
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theoretical model. We find a magnetic field $B > 0.1 \nu_{18}^{-1/3}$ G, electron Lorentz factor $\gamma > 3.06 \times 10^2 \nu_{18}^{1/3}$ and radius of the emitting region $R \leq 6.92 \times 10^{15}$ cm. (iv) The DCF technique was applied to the hard (2–10 keV) and soft (0.3–2 keV) X-ray bands and displayed positive correlations with no time lag. This implies that the emission in both nearby bands arose from the same production region at the same time; i.e., there is no evidence that the softer X-rays arise from synchrotron emission while the harder come from SSC. (v) A hardness ratio analysis was also employed to study spectral variations. HRs showed flatter spectra at high fluxes (Fig. 2). This indicated that the HR normally increased with increasing flux and got “harder-when-brighter”. Fig. 5 displays more information about the spectral evolution of the source. During these extended observations, a few epochs had hard-lags, pointing to the particle acceleration mechanism being responsible for the X-ray emissions, whereas a few epochs had soft-lags, indicating that X-rays are predominantly emitted by the synchrotron cooling mechanism during those periods.

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