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Unprecedented X-ray Flaring Activity of Mrk 421 in 2013 April

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Mrk 421 showed an unprecedented X-ray flaring behaviour in 2013 April 10–17 when the consecutive outbursts by a factor of 8–16 were observed in the 0.3–10 keV and 3–79 keV bands, and it became one of the brightest objects in the X-ray sky. During these events, the source was also very active on intraday timescales with fractional variability amplitude of 2–47 per cent, and showed the flux doubling and halving time scales of 1.16–7.20 hr and 1.04–3.54 hr, respectively. We have revealed up to 20 cases when the flux varied with 3σ significance within 1 ks. In this period, Mrk421 also underwent the most extreme X-ray spectral variability ever reported for BL Lacertae objects. The location of the synchrotron SED peak moved from about 0.1 keV to almost 20 keV. The photon index at 1 keV and curvature parameter showed the ranges a=1.68–2.83 and b=0.09–0.57, respectively, and varied along with the flux on diverse time scales down to the intervals shorter than 1 ks. While the X-ray outburst were accompanied by very strong TeV-flares, the source was relatively less active in the radio-UV and GeV energy ranges.

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1. Introduction

BL Lacertae objects (BLLs) are active galactic nuclei (AGN) of elliptical galaxies, which with quasi-featureless spectra, high and variable optical/radio polarization, compact radio-morphology, strong flux variability in all spectral bands and broad continuum extending from radio to very high energy γ-rays. These properties are explained as a result from a relativistically boosted non-thermal emission produced in the jet closely aligned to the line-of-sight (see [1] and references therein). Their spectral energy distribution (SED) shows the presence of two broad components. The lower-energy one is explained via the synchrotron radiation emitted by relativistic electrons in the jet, while the inverse Compton (IC) scattering of synchrotron photons (produced locally, or having an external origin) by the same electron population and hadronic processes are considered as possible sources for the high-frequency bump [2].

In the following, some results from the timing and spectral study of the unprecedented X-ray flaring activity of Mrk 421 in 2013 April are presented.

2. High-energy Flux Variability from Past Studies

Mrk 421 is a nearby (z=0.031, [3]) high-energy peaked BL Lac object (HBL) which was the first TeV-detected extragalactic object [4]. This detection was followed by numerous multiwavelength (MWL) campaigns which revealed an extreme X-ray and TeV variability in this object. Their highlights are briefly reviewed in the next two subsections.

2.1 TeV-band Variability

- Whipple observations of 1994 May 9-10 revealed an increase in the TeV flux by a factor of ∼10 compared to its quiescent level [5].

- The 1995 April-May MWL campaign showed a rapid variations in the TeV light curve with doubling and decay times of about 1 d [6].

- The source underwent an extremely rapid VHE flares on 1996 May 7. In the first outburst, which had a doubling time of about one hour, the flux increased above the relatively quiescent value by more than a factor of 50, making Mrk421 the brightest TeV source in the sky. In the second outburst, which lasted about 30 min, the flux increased by a factor of 20–25 [7].

- Strong TeV outbursts during December 1999 – May 2001 were reported by [8] from the HEGRA observations, accompanied by a rapid variability with the flux doubling time of 20 min.

- Whipple observations in 2000–2001 revealed exceptionally strong and long-lasting flaring activity with the TeV flux of 0.4–13 Crab [9].

- Several strong TeV flares in Mrk 421 was reported by [10] from the observations with Tibet III air shower array, Whipple, HEGRA and CAT in 2000–2001.

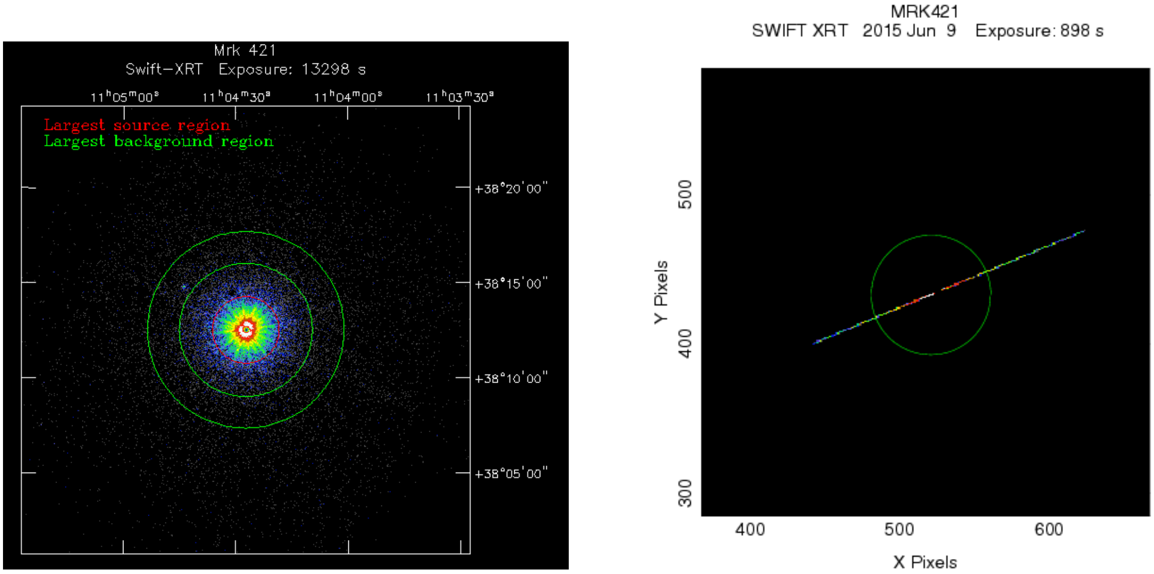

Figure 1: X-ray images of Mrk 421 from the *Swift*-XRT observations peromed in the photon counting (PC; left) and windowed timing (WT; right) regimes.

- Mrk 421 was detected in an extraordinarily high state at TeV energies with CANGAROO-II in 2001 January–March [11]. The same was reported by [12] from the 2000 February–May campaign with HEGRA. The TeV observations on February 7/8 showed a substantial TeV flux variability on the 30 min timescale.
- During the 2006 April–June monitoring, the TeV flux doubling time of 36 min was observed with MAGIC [13].
- On 2008 May 2/3, bright flares were detected with the TeV fluxes reaching the level of 10 Crab [14].

2.2 X-ray Variability

- *BeppoSAX* observations in 1998 April revealed multiple flares, occurring on timescales of about 1 day [15].
- Target of Opportunity (ToO) observation of Mrk 421 with *BeppoSAX* in 1998 June revealed the source in a high and hard X-ray state with a significant temporal and spectral variability on timescales down to 500–1000 s [16].
- *BeppoSAX* observations in 1997–2000 showed a variability in the 15–90 keV count rate by a factor of 33.4 [17].
- The three *XMM-Newton* pointings performed in 2000–2004 showed significant spectral variations on time scales as short as $\sim$500–1000 s [18].
- The 3–20 keV flux from the *RXTE*-PCA observations in 2000 February–May increased and decayed with e-folding times as short as about 5 hr [12].

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- *Swift*-XRT observations in 2005 March–July showed large variations in the 2–10 keV flux, by a factor of about 20 [19].
- From the *NuSTAR* observations in 2013 April, Paliya et al. [20] reported about the detection of the shortest flux doubling time of 14.01±5.03 min, which is the shortest hard X-ray (3–79 keV) variability ever recorded for Mrk 421.

3. Results

For our study, we used the *Swift*-XRT and *NuSTAR* data, retrieved from the publicly available archive, maintained by HEASARC[1], and processed according to the standard `HEASOFT` procedures described in detail in [21]. For the observations showing the count rates above 100 cts s^{-1}, a pileup correction was performed according to the recipe presented in [22].

3.1 Flux Variability

The source exhibited an unprecedented X-ray flaring behaviour in April 10–17, when we observe the two consecutive outbursts by a factor of 12 and 8.1 in the 0.3–10 keV band (followed by a minor flare). The count rate exceeded the level of 200 cts s^{-1} for the first time since the start of the *Swift* observations of Mrk 421, and it became one of the brightest sources in the X-ray sky (see Fig. 2a).

In the 3–79 keV band, we observe the three strong flares (Fig. 2b), and Mrk 421 was detected by *MAXI* with 5σ significance every day in this period.

The source showed several X-ray flux doubling/halving events during 2013 April 10-17. For example, The 3–79 keV count rate showed an increase by a factor of 8.84 in 23.6 hr, superimposed by a minor flare during the prolonged *NuSTAR* observation on April 11/12. Mrk 421 exhibited two successive flares by a factor of 1.74 and 2.75 in 4.7 hr and 6.3 hr, respectively, reaching the highest historical 0.3–10 keV count rate on April 12/13.

The fastest events X-ray flux variability is found from the separate orbits of the XRT observation ObsID 00080050019 (April 12/13), each lasting less than 1 ks and exhibiting a flux variability with 99.9% confidence with fractional variability amplitude of 2.2(0.4)%–5.9(0.3)% (Fig. 2c)[2].

A strong TeV flaring behaviour was also evident from the MAGIC and FACT observations (see [21]). The optical–UV light curves sometimes showed an uncorrelated behaviour with the X-ray ones. The *Fermi*-LAT (0.3–300 GeV) flux from this period was not the highest in the first half of 2013 [21].

3.2 X-ray Spectroscopy

We performed the X-ray spectral analysis by fixing the Hydrogen column density to the Galactic value $N_{\rm H} = 1.90 \times 10^{20}$ cm^{-2}, taken from Leiden/Argentine/Bonn (LAB) Survey of Galactic HI [23], and using the log-parabolic model (LP; [17])

$$F(E) = K(E/E_1)^{-(a+blog(E/E_1))} \text{ ph cm}^{-2} \text{ s}^{-1} \text{ keV}^{-1}, \tag{3.1}$$

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

[2] A comprehensive and detailed description of the X-ray flux and spectral variability of Mrk 421 in the 2013 April 10–17 period is presented in [21].

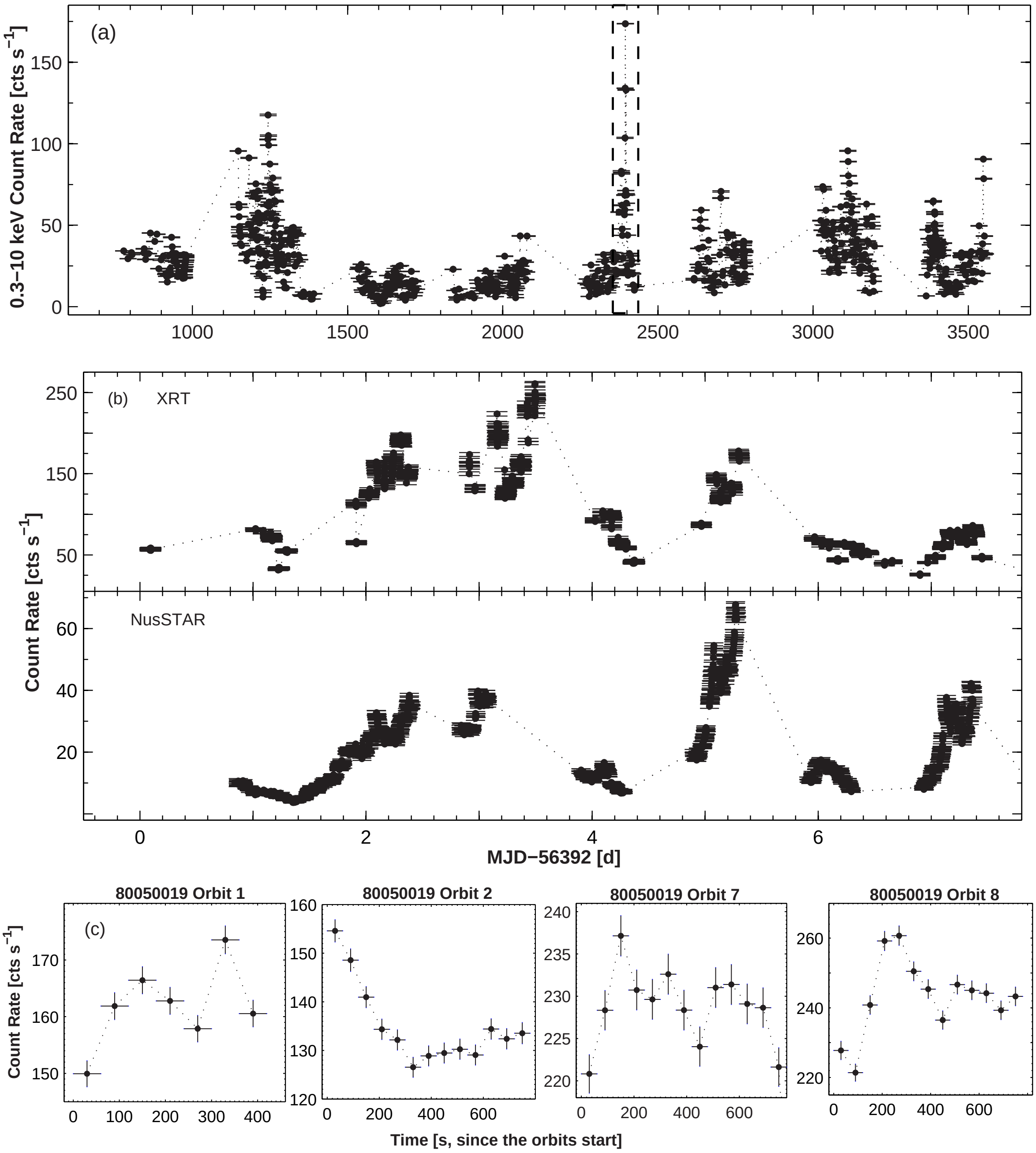

Figure 2: (a) Long-term 0.3–10 keV light curve of Mrk 421 from the *Swift*-XRT observations in 2005-2016 with the dashed area representing the giant outbursts of 2013 April 10–17; (b) the XRT and *NuSTAR* light curves of Mrk 421 from the 2013 April 10–17 period; (c) fastest X-ray flux variability detected from different orbits of ObsID 00080050019.

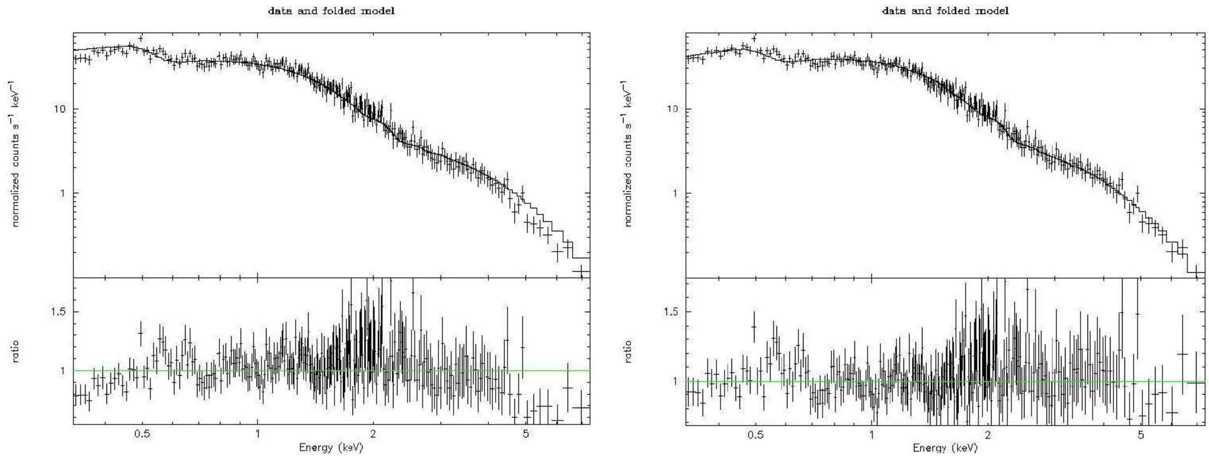

Figure 3: The powerlaw (left) and logparabolic (right) fits to the spectrum of Mrk 421 extracted from the second orbit of the *Swift*-XRT pointing ObsID 00080050016 (April 11). In the first case, the reduced Chi-square is 1.283 with 244 d.o.f., while it is equal to 0.932 with 242 d.o.f. for the logparabolic fit. In the second case, the curvature parameter is significant (b=0.36$\pm$0.04), and the distribution of the fit residuals show that the logparabola model is acceptable for this spectrum, while the powerlaw fit yields a prominent trend in the residuals.

with E_1, the pivot energy fixed to 1 keV and 10 keV for the XRT and *NuSTAR* spectra, respectively; a, the photon index at the energy E_1; b, the curvature parameter; K, the normalization factor. During 2013 April 10–17, the source also underwent the most extreme X-ray spectral variability ever reported for BLLs. The spectra mainly were curved and fitted well with the LP model (see Fig. 3 for the corresponding example). In the case of the XRT spectra, the location of the synchrotron SED peak moved from about 0.1 keV to almost 20 keV. The photon index at 1 keV and curvature parameter showed the ranges a=1.68–2.83 and b=0.09–0.47, respectively, and varied along with the 0.3–10 keV flux on different time scales from a few weeks down to intervals shorter than 1 ks. The curvature parameter showed an even larger range of 0.13–0.57 in the 3–79 keV band.

However, some XRT and NuSTAR spectra showed the values of the curvature parameter below b=0.08, and the fit with the LP model did not give better statistics than that with the simple power-law (PL) $F(E) = KE^{-\Gamma}$, where Γ is the photon index throughout the observation band. Therefore, the latter model was chosen for those spectra (see Fig. 4). The parameter Γ also showed broad ranges Γ=1.70–2.76, and Γ=2.38–3.16 for the XRT and *NuSTAR* spectra, respectively.

4. Conclusions

- Mrk 421 showed an unprecedented X-ray flaring behaviour in 2013 April 11–16 when the consecutive outbursts by a factor of 8–16 were observed in the 0.3–10 keV (*Swift*-XRT) and 3–79 keV (*NuSTAR*) bands.

- The 0.3–10 keV count rate exceeded the level of 200 cts s^{-1} for the first time since the start of the Swift observations of Mrk 421, and it became one of the brightest objects in the X-ray sky.

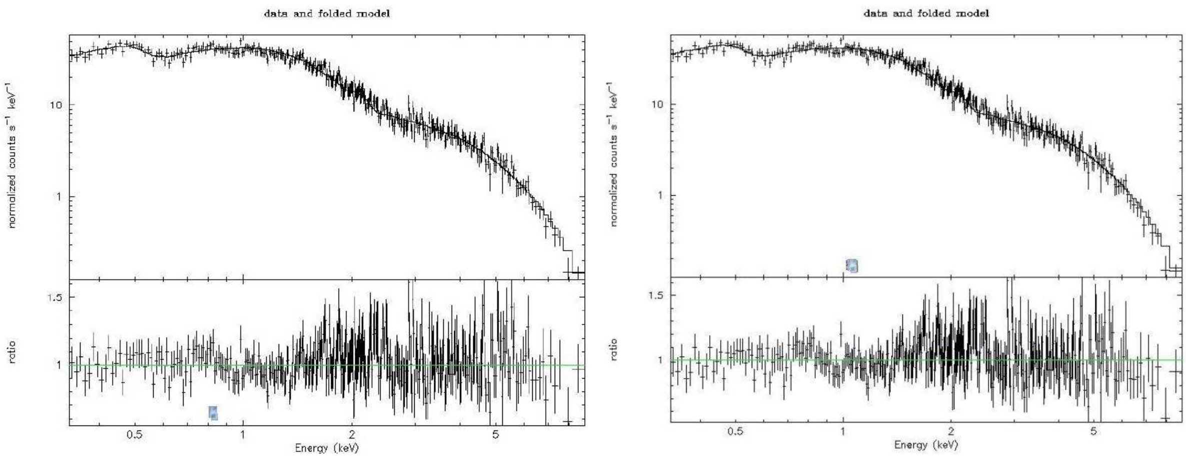

Figure 4: Same as Fig. 3 from the first 300 s segment of the second orbit of the *Swift*-XRT pointing ObsID 00035014063 (April 14/15). In the first case, the reduced Chi-square is 0.921 with 329 d.o.f., while it is equal to 0.908 with 328 d.o.f. for the logparabola fit. In the second case, the curvature parameter is very small (b=0.06±0.03), hinting on the insignificant spectral curvature. Therefore, we chose the powerlaw model for this spectrum.

- During these events, the source was also very active on intraday timescales with fractional variability amplitudes of 2–47 per cent, and showed the flux doubling and halving time scales of 1.16–7.20 hr and 1.04–3.54 hr, respectively.

- We have revealed up to 20 cases when the flux varied with 3 sigma significance within 1 ks, and numerous IDVs occurring within 1 hr.

- In this period, Mrk421 also underwent the most extreme X-ray spectral variability ever reported for blazars. The location of the synchrotron SED peak moved from about 0.1 keV to almost 20 keV. The photon index at 1 keV and curvature parameter showed the ranges a=1.68–2.83 and b=0.09–0.57, respectively, and varied along with the flux on diverse time scales down to the intervals shorter than 1 ks.

- While the X-ray outburst were accompanied by strong TeV-flares, the source was less active in the radio–UV and GeV energy ranges that that can be explained via the global long-term change in the efficiency of the acceleration mechanism, shifting the entire synchrotron bump to higher energies.

5. Acknowledgements

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DISCUSSION

JIM HOWARTH BEALL: What was the source of your Inverse Compton "seed"photons?

Sergo KAPANADZE: We adopted so-called synchrotron self-Compton scenario when the low-energy photons are up-scattered by the same electron population which produce them via the synchrotron mechanism.