INVERSE COMPTON X-RAY EMISSION FROM TeV BLAZAR MRK 421 DURING A HISTORICAL LOW-FLUX STATE OBSERVED WITH NuSTAR

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**ABSTRACT**

We report on the detection of excess hard X-ray emission from the TeV BL Lac object Mrk 421 during the historical low-flux state of the source in 2013 January. Nuclear Spectroscopic Telescope Array observations were conducted four times between MJD 56294 and MJD 56312 with a total exposure of 80.9 ks. The source flux in the 3–40 keV range was nearly constant, except for MJD 56307 when the average flux level increased by a factor of three. Throughout the exposure, the X-ray spectra of Mrk 421 were well represented by a steep power-law model with a photon index of $\Gamma \approx 3.1$, although a significant excess was noted above 20 keV in the MJD 56302 data when the source was in its faintest state. Moreover, Mrk 421 was detected at more than the 4σ level in the 40–79 keV count maps for both MJD 56307 and MJD 56302 but not during the remaining two observations. The detected excess hard X-ray emission connects smoothly with the extrapolation of the high-energy γ-ray continuum of the blazar constrained by Fermi-LAT during source quiescence. These findings indicate that while the overall X-ray spectrum of Mrk 421 is dominated by the highest-energy tail of the synchrotron continuum, the variable excess hard X-ray emission above 20 keV (on the timescale of a week) is related to the inverse Compton emission component. We discuss the resulting constraints on the variability and spectral properties of the low-energy segment of the electron energy distribution in the source.

**Key words:** acceleration of particles – BL Lacertae objects: individual (Mrk 421) – galaxies: active – galaxies: jets – radiation mechanisms: non-thermal

1. INTRODUCTION

Blazars are a subclass of radio-loud active galactic nuclei for which non-thermal jet emission is relativistically beamed along the line of sight (for a review see, e.g., Begelman et al. 1984; Urry & Padovani 1995). Thus, pronounced variability on timescales as short as days and even hours is often observed in various energy bands (e.g., Wagner & Witzel 1995; Ulrich et al. 1997). The broadband electromagnetic spectra of blazars consist of two characteristic bumps in the $\nu - \nu F_{\nu}$ representation: one extending from radio to optical/X-ray frequencies and the other one peaking around high-energy γ-ray photon energies. The measured polarization in the radio and optical bands indicates that the low-energy spectral component is due to the synchrotron emission of ultrarelativistic electrons; the γ-ray continuum is instead most widely believed to result from the inverse Comptonization (IC) of various soft photon fields. The source of the seed photons for the IC process can be either the synchrotron emission of the jet itself (“Synchrotron self-Compton” model), or SSC for short; e.g., Jones et al. 1974; Marscher 1980; Band & Grindlay 1985), or the thermal emission of circumnuclear gas and dust (e.g., Dermer & Schlickeiser 1993; Sikora et al. 1994; Inoue & Takahara 1996). There is an ongoing debate concerning the exact localization of the dominant blazar emission zone, with current estimates ranging from hundreds of gravitational radii from central supermassive black holes up to parsec-scale distances, as well as on the dominant particle acceleration processes involved, with different scenarios including mildly relativistic internal shocks (e.g., Böttcher & Dermer 2010; Mimica & Aloy 2012; Saito et al. 2015), magnetic turbulence (e.g., Yan et al. 2013; Asano et al. 2014; Zheng et al. 2014; Kakuv et al. 2015), or even relativistic magnetic reconnection (e.g., Bieteau & Giebels 2012; Narayan & Piran 2012; Sironi et al. 2015).

Mrk 421 (R.A. = 11$^{\mathrm{h}}$04$^{\mathrm{m}}$27$^{\mathrm{s}}$ ; decl. = +38$^{\circ}$12'32"; z = 0.031) is a nearby, bright blazar classified as a typical “high-frequency-peaked” BL Lac (HBL) object whose synchrotron and IC emission components extend up to the X-ray and very high-energy γ-ray photon energies, respectively. In fact, it is the first extragalactic source detected in the TeV range (Punch et al. 1992). As such, Mrk 421 is one of the most comprehensively studied HBLs thanks to a number of observation campaigns. In particular, recent multi-wavelength campaigns, including Fermi-LAT, have provided the first ever complete coverage of the γ-ray continuum of the source in its low-activity/quiescent state (Abdo et al. 2011b). Interestingly, the fractional variability amplitude $F_{\text{var}}$, when plotted as a function of frequency, also reveals a double-peaked structure echoing the spectral energy distribution (SED) of Mrk 421: $F_{\text{var}}$ rises significantly from the radio toward the X-ray frequencies, decreases over the Fermi-LAT band, and finally rises again in the TeV regime (Abdo et al. 2011b; Baloković et al. 2016). This finding seems to imply that in the framework of the “homogeneous one-zone” emission model, the high-energy tail of the electron energy distribution (synchrotron X-rays and TeV γ-rays emitted via the IC process) is highly variable, while the low-energy segment of the electron energy distribution is relatively steady. The alternative interpretation is a stratified (multi-zone) blazar emission model with highly variable high-energy emission produced in distinct (more compact) emission sites compared with lower-energy emission which varies more slowly.

In this context, broadband X-ray observations of Mrk 421 may in principle provide unique clues concerning the variability and spectral properties of both the lowest- and highest-energy segments of the electron energy distribution because the synchrotron continuum of the blazar falls exponentially around
Table 1
Summary of NuSTAR Observations and Analysis of Mrk 421

| Start Time  | Exposure | model | $\Gamma_1^a$ | $E_{\text{brk}}^b$ (keV) | $\Gamma_2^c$ | 3–79 keV energy flux (10^{-12} erg cm^{-2} s^{-1}) | $\chi^2$/ dof |
|------------|----------|-------|-------------|-----------------|-------------|----------------|---------------|
| MJD 56294.78 | 9.2      | PL $^d$ | 3.10 ± 0.03 | ...             | ...         | 44.4 ± 0.6     | 170.8/161    |
|            |          | BKN-PL $^e$ | 3.25 ± 0.05 | 7.23 ± 0.66     | 2.87^{+0.06}_{-0.07} | 46.4 ± 4.2    | 155.1/159    |
|            |          | PL+PL $^f$ | 3.32 ± 0.07 | ...             | 1.7          | 48.4 ± 0.9     | 158.1/160    |
| MJD 56312.05 | 22.6     | PL     | 3.06 ± 0.02 | ...             | ...          | 31.0 ± 0.3     | 262.3/249    |
|            |          | BKN-PL  | 3.08 ± 0.02 | 17.8^{+2.1}_{-1.6} | 2.08^{+0.26}_{-0.23} | 34.0 ± 1.3    | 246.3/247    |
|            |          | PL+PL   | 3.11^{+0.04}_{-0.03} | ...       | 0.17^{+0.71}_{-0.79} | 35.3 ± 0.5    | 247.9/247    |
| MJD 56307.04 | 24.2     | PL     | 3.03 ± 0.01 | ...             | ...          | 107.6 ± 0.5    | 467.4/456    |
|            |          | BKN-PL  | 2.96 ± 0.02 | 7.83^{+0.7}_{-0.5} | 3.19^{+0.04}_{-0.03} | 105.1 ± 3.3   | 429.6/454    |
| MJD 56312.10 | 25.0     | PL     | 3.07 ± 0.02 | ...             | ...          | 36.4 ± 0.3     | 295.3/290    |
|            |          | BKN-PL  | 3.07 ± 0.02 | 28.8^{+9.2}_{-5.2} | 1.78^{+0.81}_{-0.78} | 38.2 ± 1.2    | 292.5/288    |

Notes.

$^a$ The power-law index for the PL model, the low-energy power-law index for the BKN-PL model, or finally the power-law index for the first PL components in the PL+PL model.

$^b$ The break energy for the BKN-PL model in keV.

$^c$ The high-energy power-law index for the BKN-PL model, or the power-law index for the second PL components for the PL+PL model.

$^d$ The power-law model, WABS*PEGP, where the absorption column density was fixed to the Galactic value.

$^e$ The broken power-law model, WABS*BKENPOWER, where the absorption column density was fixed to the Galactic value.

$^f$ The double power-law model, WABS*(PEGP+PEGP), where the absorption column density was fixed to the Galactic value.

photon energies of several/tens of keV (at least during the low-activity states). This reflects the high-energy cutoff in the underlying electron energy distribution, and so the radiative output of the source in the hard X-ray range may be dominated by the low-energy tail of the IC emission component. However, in the case of BL Lac objects in general and HBLs in particular, including the X-ray brightest source Mrk 421, X-ray data above 10 keV are deficient and available typically only for isolated flaring periods (see Ushio et al. 2009, 2010; Abdo et al. 2011b). This is because previous hard X-ray observations relied on “non-imaging” detectors for which the sensitivity was insufficient to detect the source in its low-activity states. The Nuclear Spectroscopic Telescope Array (NuSTAR; Harrison et al. 2013) mission is the first focusing high-energy X-ray telescope in orbit and operates in the band from 3 to 79 keV. Thanks to its imaging capability, NuSTAR probes the hard X-ray sky with a more than 100-fold improvement in sensitivity.

Paliya et al. (2015) and Sinha et al. (2015) presented the NuSTAR observations of Mrk 421 during flaring epochs. In this paper, we revisit the archival Mrk 421 data provided by NuSTAR in 2013 January and discussed previously by Baloković et al. (2016) when the source was in a historical low-activity state corresponding to an extrapolated 2–10 keV energy flux of $\approx 4 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$.

2. OBSERVATIONS AND RESULTS

2.1. Observation and Data Reduction

Mrk 421 was selected as a representative of the HBL class of blazars, and thus has been observed frequently with NuSTAR since 2013 January, partly in the framework of extensive multifrequency campaigns. The total exposure time over 88 orbits amounts to more than 250 ks, including two calibrating observations conducted in 2012 July (Baloković et al. 2016). A typical NuSTAR observation spans 10 hr; hence, the actual exposure for each observation, after only “good time intervals” are selected to eliminate the passage of the South Atlantic Anomaly and orbital modulation of visibility, ranges from 10 to 25 ks. All observations were conducted with two co-aligned independent telescopes called Focal Plane Module A and B (FPMA and FPMB). Throughout the observations, variations in the count rate of more than two orders of magnitude were observed. It has been argued that the synchrotron emission of the blazar accounts for all of the flux detected up to 79 keV during the flaring states (Paliya et al. 2015; Sinha et al. 2015).

Here, we focus on the historical low-flux state of Mrk 421, which was witnessed by NuSTAR in 2013 January (see Table 1 for the logs of the analyzed observations).

The archival NuSTAR data were downloaded from NASA’s HEASARC interface and reduced using the NuSTARDAS software, which is included as part of the HEAsoft package version 6.17. For the temporal and spectral studies presented in the following sections, the X-ray events were extracted from a circular region with a radius of 30" and centered on the source position, whereas the background was accumulated in an annulus with inner and outer radii of 30" and 70", respectively. We carefully checked that other choices of source and background regions did not affect the analysis results presented in the next sections within uncertainties of 1σ. The response files were generated by using the standard nupipeline and nuproducts scripts. Version 20151008 of the CALDB files were used in this study. Even in the historical low-flux state of the target, the extracted X-ray count rates were well above the background level up to 40 keV and almost equal to the background level above 40 keV. With good characterization of the NuSTAR background, which left the uncertainty at a 1% level (Wik et al. 2014), the gathered Mrk 421 data could therefore be used for spectral modeling up to the high-energy end of the NuSTAR band at 79 keV.

2.2. Analysis Results

Figure 1 shows the count rate variations during the NuSTAR observations between January 2 (MJD 56294) and January 20 (MJD 56312). The X-ray counts from both the FPMA and FPMB detectors are summed and the background is subtracted.

http://heasarc.gsfc.nasa.gov/docs/archive.html
The light curves are shown separately for the two different energy bands: 3–40 keV (top panels) with 2 ks binning and 40–79 keV (bottom panels) with 20 ks binning. The light curves indicate that the 3–40 keV source flux was nearly constant, except for MJD 56307 when a pronounced variability was observed and the average flux increased by a factor of three. In addition, note that the source was detected at more than the 3σ level in the 40–79 keV band not only in MJD 56307 but also in MJD 56302, when an average 3–40 keV count rate was lowest. For the remaining two observations, we provide the corresponding 95% confidence level upper limits.

Figure 2 compares the temporal variations in the NuSTAR X-ray images of Mrk 421 in the 40–79 keV energy range. These were reconstructed by using the sum of the FPMA and FPMB data from MJD 56294, 56302, 56307, and 56312, respectively. The images were smoothed by a Gaussian kernel of 19″6 and color-coded; the given color bar indicates a relative excess of photon counts in arbitrary units for which the maximum value is corrected for different exposure times of each observation (see Table 1). Note that the target was clearly detected at more than the 4σ level in MJD 56302 and 56307, which is consistent with the source light curve given in Figure 1. A slightly higher significance for the images (>4σ) compared to the light curves (>3σ) is because source counts were extracted from a circular region with a radius of 30″ for Figure 1, whereas all of the detected photons were used for Figure 2 against the point-spread function of NuSTAR. A positive detection of the source above 40 keV during the extremely low-flux state in MJD 56302 but not during the similarly low-flux states in MJD 56294 and 56312 indicates that the excess hard X-ray emission is variable on the timescale of a week.

For the spectral fitting, we binned the source light curve to a minimum of 40 counts per bin to enable the χ² minimization statistics. Table 1 lists the resulting fitting parameters for all of the analyzed observations, for which errors are quoted at the 1σ confidence level. The Galactic absorption column density toward Mrk 421 was taken to be $N_H = 1.5 \times 10^{20}$ cm$^{-2}$ (Elvis et al. 1989). Figure 3 shows the FPMA (black symbols) and FPMB (red symbols) spectra during MJD 56302 plotted against the best-fit power-law (PL) model, broken power-law (BKN-PL) model in which the high-energy photon index is harder than that in the low-energy part, and double power-law (PL+PL) model within the energy range of 3–79 keV. The residuals in the figure corresponding to the PL fit (best-fit photon index $\Gamma = 3.10 \pm 0.03$ with $\chi^2$/dof of 262.3/249) indicate that the source spectrum exhibits significant hard excess emission above 20 keV.
The fits significantly improved in the cases of both the BKN-PL and PL+PL models ($\chi^2$/dof of 246.3/247 and 247.9/247, respectively). Thus, the improvement in the $\chi^2$ statistic as measured with the $F$ static value of 8.0 was significant at more than the 99.9% level using the $F$-test. Spectral hardening was statistically less significant in the MJD 56294 and 56312 data (see Table 1).

3. DISCUSSION AND CONCLUSION

In the previous sections, we presented an analysis of the archival NuSTAR observations of Mrk 421 in 2013 January when the overall X-ray flux was particularly low. In MJD 56032, the 2–10 keV energy flux estimated from the extrapolation of the PL fit (photon index $\Gamma \approx 3.1$) was $(4.02 \pm 0.05) \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$, which is the lowest ever reported in the literature for the source. The detection of Mrk 421 above 40 keV in such a low-flux state manifested in a concave broadband X-ray spectrum of the target with excess hard X-ray emissions dominant at photon energies above 20 keV (Table 1 and Figure 3). However, this excess was not found in the MJD 56294 or 56312 data when the source was in a similarly low-flux state (Figures 1 and 2), which implies a variability of the hard X-ray continuum on the timescale of a week.

Figure 2. Temporal variations in the NuSTAR images of Mrk 421 in the 40–79 keV energy range. The images denote the relative excess of photon counts (arbitrary units indicated in the color bar corrected for difference in exposures; see Table 1) smoothed with a Gaussian kernel of 19$''$. The photon counts from FPMA and FPMB are summed. Note that the source was significantly detected at more than the 4\(\sigma\) level only in MJD56302 and MJD56307, which is consistent with the source light curve given in Figure 1.

Figure 3. NuSTAR spectrum of Mrk 421 from the MJD 56302 data. The upper panel presents the FPMA (black) and FPMB (red) data plotted against an absorbed power-law model with the photon index $\Gamma \approx 3.1$ and the Galactic column density of $N_H = 1.5 \times 10^{20}$ cm$^{-2}$, fit over the 3–79 keV band. The bottom panels show the data/model ratio residuals for the power-law (PL) fit, broken power-law (BKN-PL) fit, and double power-law (PL+PL) fit. Deviations above 20 keV are clearly seen in the PL fitting, as detailed in the text.
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To investigate the physical origin of the detected excess emission, we compiled the broadband X-ray (NuSTAR; this work) and high-energy γ-ray (Fermi-LAT; Abdo et al. 2011b) data in a $\nu - \nu F_\nu$ representation, as shown in Figure 4. Bow-ties plotted in black denote the Fermi-LAT data taken during different multi-frequency campaigns; the average source spectrum during the period of a source quiescence (from 2008 August 5 to 2010 February 20) is shown as a magenta bow-tie. The dashed magenta lines mark the extrapolation of the best-fit power-law model to the average Fermi-LAT data (γ-ray photon index of 1.78 ± 0.02).

Interestingly, similar spectral upturns related to the synchrotron/IC crossover have been detected below 10 keV in several other blazars classified as “low-frequency-peaked” BL Lacs (LBLs; see, e.g., Tagliaferri et al. 2000; Tanisata et al. 2003; Wierzboska & Wagner 2016) but never in HBLs either below or above 10 keV. What provides further novelty here is that the high-energy excess feature found in the NuSTAR data for Mrk 421 is variable on the timescale of a week; no evidence for such variability in the low-energy segment of the IC emission continuum has been reported for other BL Lac objects in the literature.

An alternative explanation for the observed hard X-ray excess of the target is spectral pile-up in the electron distribution $N'_e(\gamma_e)$, where $\gamma_e$ is the electron Lorentz factor, forming temporarily at the highest energies.4 This feature may appear due to either (i) a continuous (stochastic) acceleration of electrons limited by radiative losses (e.g., Stawarz & Petrosian 2008), or (ii) the reduction of the IC cross-section in the Klein–Nishina regime (e.g., Moderski et al. 2005). In case (i), the pile-up bump appears at the maximum electron energies for which the acceleration timescale equals the radiative loss timescale at the limit for the perfect confinement of electrons within the emission zone (i.e., no particle escape). However, the PL tail at lower electron energies has to be relatively flat in such a scenario, $s \equiv -d \ln N'_e(\gamma_e)/d \ln \gamma_e = 0 - 1$, which disagrees with the observation in Mrk 421. Similarly, in case (ii), the necessary condition for the formation of a pronounced spectral hardening in the electron energy distribution is the dominance of IC cooling over synchrotron cooling and a relatively narrow (within the frequency range) seed photon distribution. These requirements contradict the conditions expected for the Mrk 421 jet in quiescence (for which the synchrotron losses dominate the IC losses and the soft photon distribution for the IC scattering is provided by the broadband synchrotron emission of the jet itself).

From the observed SSC photon energy of $h\nu_{ssc} \approx 20$ keV and a steep broadband PL electron energy distribution, the corresponding minimum electron Lorentz factor is roughly

$$\gamma_{e, \text{min}} \sim 10^7 \left( B^2 \over 0.1 \text{ G} \right)^{-1/4} \left( \delta / 10 \right)^{-1/4} \text{ s}. \quad (1)$$

The radiative cooling timescale for such low-energy electrons dominated by the synchrotron process is then

$$\tau_{\text{cool}}(\gamma_{e, \text{min}}) \sim 10^7 \left( B^2 \over 0.1 \text{ G} \right)^{-7/4} \left( \delta / 10 \right)^{-3/4} \text{ s}, \quad (2)$$

which is much longer than a week for the comoving magnetic field intensity $B \lesssim 0.1$ G emerging from the one-zone SSC model applied to the quiescence SED of Mrk 421 (Abdo et al. 2011b). Hence, the variability of the low-energy electrons implied by the NuSTAR observations analyzed in this paper have to be related to dynamical changes within the blazar emission zone for which the shortest timescale is given by the light crossing time $R/c$. Interestingly, this would agree with the emission region size assumed in the SED model of Abdo et al. (2011b). In particular, one has

$$R \approx 0.06 \left( t_{\text{var}} \over 1 \text{ week} \right) \left( \delta / 10 \right) \text{ pc}, \quad (3)$$

which implies the distance of the emission zone from the active nucleus $r \sim \Gamma_j R \approx 0.6$ pc for the anticipated conical jet geometry with the opening angle $\sim 1/\Gamma_j$ and the jet bulk Lorentz factor $\Gamma_j \sim 10$. This is also in accord with the detailed analysis of the overall variability of Mrk 421 at X-ray frequencies, which implies that the power in the intraday flickering of the source is small (Kataoka et al. 2001; Isobe et al. 2015).

In addition, the results of our NuSTAR data analysis revealed that the electron energy distribution in Mrk 421 during source quiescence is well represented by a relatively steep PL with an energy index of $s \approx 2\Gamma_\gamma - 1 \sim 2.6$, which extends from

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4 Here, we do not consider the possibility that the observed hard X-ray excess is related to the bulk Comptonization of the accretion disk emission by cold electrons within the innermost parts of the Mrk 421 jet, since the corresponding bulk-Compton spectral features have been predicted for (and possibly even observed in) luminous blazars of the “flat-spectrum-radio-quasar” type (see, e.g., Sikora et al. 1997; Kataoka et al. 2008 and references therein), and not for BL Lac objects characterized by low accretion rates, and hence radiatively inefficient accretion disks.
electron energies of at least $\gamma_e \sim 10^3$ up to $\gamma_e \sim 10^6$ (in the jet rest frame). This is an important finding because in such a case the bulk of the jet kinetic energy is carried by those low-energy electrons (assuming no significant proton content). The exact value of the electron spectral index is also important based on the most recent results for the kinetic simulations of relativistic magnetic reconnection process. In other words, the PL energy spectra formed within the reconnection sites are steep ($s > 2$ only if the jet magnetization is low; Sironi & Spitkovsky 2014; Guo et al. 2015). Again, the low magnetization of the emission region would be in agreement with the model parameters emerging from a simple one-zone SSC model (Abdo et al. 2011a, 2011b). However, note that this conclusion is only with regard to the slowly variable/quiescence emission component because the production of rapid high-amplitude flares in blazar sources may proceed under very different conditions and may involve very different electron spectra.

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