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<th>FirstNuSTAR observations of MRK 501 within a radio to TeV multi-instrument campaign</th>
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<td>Connolly, M.P.; Gillanders, Gary; Lang, Mark</td>
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FIRST NuSTAR OBSERVATIONS OF MRK 501 WITHIN A RADIO TO TEV MULTI-INSTRUMENT CAMPAIGN


(The NuSTAR Team)


(The MAGIC Collaboration)


(The VERITAS Collaboration)

O. Vinge

L. Fuhrmann, E. Angelakis, V. Karamanavis, I. Myserlis, T. P. Krichbaum, J. A. Zensus

H. Underhill, S. A. Steyvers


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ABSTRACT

We report on simultaneous broadband observations of the TeV-emitting blazar Markarian 501 between 1 April and 10 August 2013, including the first detailed characterization of the synchrotron peak with Swift and NuSTAR. During the campaign, the nearby BL Lac object was observed in both a quiescent and an elevated state. The broadband campaign includes observations with NuSTAR, MAGIC, VERITAS, the Fermi Large Area Telescope (LAT), Swift X-ray Telescope and UV Optical Telescope, various ground-based optical instruments, including the GASP-WEBT program, as well as radio observations by OVRO, Metsähovi and the F-Gamma consortium. Some of the MAGIC observations were affected by a sand layer from the Sahara desert, and had to be corrected using event-by-event corrections derived with a LIDAR (Light Detection And Ranging) facility. This is the first time that LIDAR information is used to produce a physics result with Cherenkov Telescope data taken during adverse atmospheric conditions, and hence sets a precedent for the current and future ground-based gamma-ray instruments. The NuSTAR instrument provides unprecedented sensitivity in hard X-rays, showing the source to display a spectral energy distribution between 3 and 79 keV
consistent with a log-parabolic spectrum and hard X-ray variability on hour timescales. None (of the four extended NuSTAR observations) shows evidence of the onset of inverse-Compton emission at hard X-ray energies. We apply a single-zone equilibrium synchrotron self-Compton model to five simultaneous broadband spectral energy distributions. We find that the synchrotron self-Compton model can reproduce the observed broadband states through a decrease in the magnetic field strength coinciding with an increase in the luminosity and hardness of the relativistic leptons responsible for the high-energy emission.

Subject headings: galaxies: BL Lacs — galaxies: individual (Markarian 501) — X-rays
1. INTRODUCTION

Markarian 501 (Mrk 501) is a nearby, bright X-ray emitting blazar at z = 0.034, also known to emit very-high-energy (VHE; E ≥ 100 GeV) gamma-ray photons (Quinn et al. 1996). Blazars are among the most extreme astrophysical sources, displaying highly variable emission at nearly every wavelength and timescale probed thus far. These objects are understood to be active galactic nuclei that are powered by accretion onto supermassive black holes and have relativistic jets pointed along the Earth’s line of sight (Urry & Padovani 1995). Relativistic charged particles within blazar jets are responsible for the non-thermal spectral energy distribution (SED) which is characterized by two broad peaks in the νFν spectral representation. The origin of the lower-energy peak is relatively well understood, resulting from the synchrotron radiation of relativistic leptons in the presence of a tangled magnetic field (Marscher 2008). Within the leptonic paradigm, the higher-energy SED peak is attributed to inverse-Compton up-scattering by the relativistic leptons within the jet of either the synchrotron photons themselves, namely synchrotron self-Compton (SSC) emission (Maraschi et al. 1992), or a photon field external to the jet, namely external Compton (EC) emission (e.g. Dermer et al. 1992; Sikora et al. 1994). Alternatively, hadronic models attribute the higher-energy peak of blazar emission to proton synchrotron emission and/or synchrotron emission by secondary leptons produced in p-γ interactions (Aharonian et al. 2002; Bednarek 1993).

Along with the other nearby VHE blazar Mrk 421, Mrk 501 represents one of the most comprehensively studied VHE blazars. The blazar has been the subject of multiple broadband observation campaigns (e.g. Catanesi et al. 1997; Kataoka et al. 1999; Petry et al. 2004; Adho et al. 2011). Mrk 501 is one of the brightest X-ray sources in the sky, and has been observed by RXTE to display significant X-ray variability up to 20 keV (Gliozzi et al. 2006). During a phase of high activity at VHE energies in 1997, this source was also observed by BeppoSAX to display unusually hard, correlated X-ray emission up to > 100 keV, with a photon index of Γ < 2 (Pian et al. 1998).

Observations of Mrk 501 have so far lacked sufficient sensitivity at the hard X-ray energies (10-100 keV). Observations at hard X-ray energies provide direct insight into the highest energy particles through detection of synchrotron emission. There is also the possibility for insight into the lower energy particles through the detection of inverse-Compton emission from photon up-scattering by the lower-energy electrons. As a relativistic synchrotron emitter, the falling edge of the synchrotron peak mimics the energy distribution of the emitting particles, allowing the highest energy particles to be directly probed through hard X-ray observations. The energy-dependent cooling timescale can lead to more rapid variability at hard X-ray energies than at soft X-ray energies. Gliozzi et al. (2006) reported independent soft (2-10 keV) and hard (10-20 keV) X-ray variability of Mrk 501 using RXTE.

Other hard X-ray observations have previously been performed with BeppoSAX (Massaro et al. 2004a) and Suzaku HXD (Anderhub et al. 2009). Due to the rapid X-ray variability displayed by blazars such as Mrk 501, the long integration time required for significant detection and spectral reconstruction by the aforementioned X-ray instruments was not ideal for extracting information about hard X-ray variability. Much more sensitive hard X-ray observations of blazars, however, are now possible with Nuclear Spectroscopic Telescope Array NuSTAR.

NuSTAR is a hard X-ray (3-79 keV) observatory launched into a low Earth orbit in June 2012...
It features the first focusing hard X-ray telescope in orbit that allows high sensitivity beyond the 10 keV cutoff shared by all other currently active focusing soft X-ray telescopes. The inherently low background associated with concentrating the X-ray light enables NuSTAR to achieve approximately a one-hundred-fold improvement in sensitivity over the collimated and coded-mask instruments that operate in the same spectral range.

NuSTAR observed Mrk 501 four times in 2013 as part of a simultaneous multiwavelength (MWL) campaign, including VHE observations by MAGIC and VERITAS, high-energy (HE; 100 MeV-100 GeV) gamma-ray observations by the Fermi Large Area Telescope (LAT), soft X-ray and UV observations with Swift X-ray Telescope (XRT) and Ultraviolet Optical Telescope (UVOT), optical observations from a number of ground-based instruments including the GASP-WEBT program, as well as radio observations by the Owens Valley Radio Observatory (OVRO; 15 GHz), Metsähovi (37 GHz) and the F-Gamma monitoring program, providing measurements between 2.64 GHz and 228.39 GHz. The NuSTAR observations took place on 2013 April 13, 2013 May 8, 2013 July 12 and 13 (MJD 56395, 56420, 56485 and 56486, respectively), with the latter two observations resulting from target of opportunity (ToO) exposures triggered by an elevated state observed by the Swift XRT and the MAGIC telescopes.

We use these observations to study the hard X-ray spectral behavior of Mrk 501 in detail over multiple flux states. The NuSTAR observations, analysis and results are detailed in Section 2, with the contemporaneous MWL observations, analysis and results shared in Section 3. After comparing the simultaneous Swift XRT and NuSTAR observations in Section 4, we investigate variability of the source in Section 5. The MWL SEDs are constructed over the multiple observed states and investigated in terms of a single-zone equilibrium synchrotron self-Compton model in Section 6, with discussion and conclusions provided in Section 7.

2. NuSTAR OBSERVATIONS AND ANALYSIS

In order to maximize the strictly simultaneous overlap of observations by NuSTAR and ground-based VHE observatories during this broadband campaign of Mrk 501, the observations were arranged according to visibility of the blazar at the MAGIC and VERITAS sites. The NuSTAR coordinated observations involving both VERITAS and MAGIC were performed on 2013 April 13 and 2013 May 8, with the NuSTAR ToO observations (initiated by Swift and MAGIC) performed on 2013 July 12 and 13. The NuSTAR observations typically spanned 10 hours, resulting in 10-30 ks of source exposure after removing periods of orbital non-visibility. The observation details are summarized in Table 1. The data were reduced using the standard NuSTARDAS software package$^{97}$ v1.3.1.

The spectral analysis was performed with XSPEC$^{98}$ Version 12.7.1. The data were binned to require 20 counts per bin, and fit with three spectral models via $\chi^2$ minimization. The first model applied to the data is a power law

$$A(E)_{PL} = K(E/E_0)^{-\Gamma},$$

referred to as the PL model for the remainder of this work, where $F(E)$ is the flux at energy $E$, $\Gamma$ is the index, $K$ is the normalization parameter (in units of photons keV$^{-1}$ cm$^{-2}$ s$^{-1}$) and $E_0$ is fixed at 10 keV. The second spectral model applied to the data is a

![Figure 1. The spectral energy distributions of Mrk 501 derived from the NuSTAR observations, showing the PL (red), BKNPL (green) and LP (blue) models fitted to each observation. The NuSTAR observations show significant detection of the blazar up to at least 65 keV in each observation. The data-to-model ratios are shown in the bottom panel of each plot, with the spectral fit parameters summarized in Table 2. Spectra have been rebinned for figure clarity.](http://heasarc.nasa.gov/docs/software/lheasoft/xanadu/xspec/XspecManual.pdf)

$^{97}$ http://heasarc.gsfc.nasa.gov/docs/nustar/analysis/

Summary of the NuSTAR hard X-ray observations of Mrk 501. The observations are sometimes referred to with the last three digits of the Observation ID within this work.

<table>
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<tr>
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<th>Detection Range [keV]</th>
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<td>56486.8-56487.1</td>
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<td>4</td>
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Table 1

Table 2

NuSTAR spectral fit summary, with integral flux values (in units of ×10\(^{-11}\) erg cm\(^{-2}\) s\(^{-1}\)) derived from the log-parabolic fits. Data, models and ratios are shown in Figure 1. The indices of the LP fits are derived at 10 keV. The errors for each parameter are found using a value of \(\Delta \chi^2=2.706\), corresponding to a 90% confidence level for a parameter. Observation IDs are shortened by removing the first 60002024 identifier in column one.

<table>
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<th>Log Parabola</th>
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<td>Obs. Index PL Index E(_{\text{break}})</td>
<td>BKNPL Index Curvature LP</td>
<td>3-7 keV</td>
</tr>
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<td></td>
<td></td>
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<td>2.04±0.03 2.34±0.02 6.3±0.4 747/688</td>
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<td>1.90±0.02 2.25±0.02 7.4±0.3 914/861</td>
</tr>
</tbody>
</table>

broken power law, referred to as BKNPL model for the remainder of this work. The model is made up of two power-law photon indices, meeting at a break energy \(E\(_{\text{break}}\)

\[
A(E)_{\text{BKNPL}} = K(E/E_{\text{break}})^{-\Gamma_1,2}
\]

where \(\Gamma_1\) and \(\Gamma_2\) represent the photon indices below and above the break energy \(E_{\text{break}}\), respectively.

The third spectral model applied to the data is a log parabola, referred to as the LP model for the remainder of this work. This model has been suggested to better represent the X-ray spectra of TeV-detected blazars between 0.2 and 100 keV (e.g. Massaro et al. 2004; Tramacere et al. 2007a). This model allows the spectral index to vary as a function of energy according to the expression

\[
A(E)_{\text{LP}} = K(E/E_0)^{-(\Gamma+\beta \log(E/E_0))}
\]

with a curvature parameter \(\beta\). The spectral data, model fits and data-to-model ratios for each NuSTAR observation are shown in Figure 1. The spectral fitting results for each model as applied to the NuSTAR observations are summarized in Table 2. The errors for each parameter are found using a value of \(\Delta \chi^2=2.706\), corresponding to a 90% confidence level for one parameter.

For all four NuSTAR observations, the X-ray emission of Mrk 501 is best represented with a log parabola. A statistical F-test using \(\chi^2\) and degrees of freedom (DOF) of the PL versus LP fit results in F-statistics of 97.8, 129.3, 200.1 and 251.3 for the observations 002, 004, 006 and 008, respectively, corresponding to probabilities of 1.1×10\(^{-21}\), 4.6×10\(^{-28}\), 2.9×10\(^{-41}\) and 7.9×10\(^{-50}\) for being consistent with the null PL hypothesis. The broken power-law fit to the second NuSTAR observation, ID 004, produces a break energy at the lower limit of the NuSTAR sensitivity window, and is interpreted as a failed fit. The other three observations fit the break energy near \(E_{\text{break}}=7\) keV, motivating the decision to present the NuSTAR flux values in the 3-7 keV and 7-30 keV bands throughout this work. The upper bound of 30 keV is the typical orbit-timescale detection limit for the Mrk 501 observations.

The NuSTAR observations show the blazar to be in a relatively low state for the first two observations, and a relatively high state during the last two observations, with the 3-7 keV integral fluxes derived from the log-parabolic fits 2-4 times higher than found for the first two observations. More specifically, the average 3-7 keV integral flux values (in units of 10\(^{-11}\) erg cm\(^{-2}\) s\(^{-1}\)) were 3.72±0.02 and 5.19±0.02, respectively, for the observations occurring on MJD 56395 and 56420, and 12.08±0.09 and 10.75±0.05, respectively, for the observations starting on MJD 56485 and 56486. In the same flux units, the 7-30 keV integral flux values for the first two observations are similarly 3-4 times lower than the flux states observed in the last two observations (4.81±0.03 and 6.98±0.05 on MJD 56395 and 56420 as compared to 18.6±0.1 and 16.4±0.1 on MJD 56485 and 56486). These integral flux values are summarized in Table 2.

The NuSTAR observations extend across multiple occultations by the Earth, and the integral flux and index (\(\Gamma\)) light curves for the orbits of each extended observation are shown in Figure 2. The periods with simultaneous observations with the ground-based TeV instruments of MAGIC and VERITAS are highlighted by grey and brown bands in the upper portion of each light curve. The observations and results from MAGIC and VERITAS are summarized in Section 3.1.

The 3-7 keV and 7-30 keV integral flux values of the first exposure (Observation ID 002) show low variability (\(\chi^2 = 7.0\) and 13.4 for 5 DOF), while the trend of increasing flux in both the 3-7 keV and 7-30 keV bands
is clear during the second observation (Observation ID 004). The 7-30 keV flux increases from $(5.1 \pm 0.1) \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ to $(8.8 \pm 0.1) \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ in fewer than 16 hours. The 7-30 keV increases from $(1.7 \pm 0.1) \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$ to $(2.0 \pm 0.1) \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$ in fewer than 7 hours on MJD 56485 (Observation ID 006) and significantly decreases from $(1.9 \pm 0.1) \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$ to $(1.4 \pm 0.1) \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$, again in fewer than 7 hours on MJD 56486 (Observation ID 008).

The relation between the log-parabolic photon indices and 7-30 keV flux values resulting from the fits to the NuSTAR observations of Mrk 501 are shown for each observation separately in Figure 3. The curvature $\beta$ was not seen to change significantly from orbit to orbit and therefore was fixed at the average value found for each observation (see Table 2 for values). The count rate light curves show no indications of variability on a timescale of less than an orbit period ($\sim$90 minutes). As observed previously in the X-ray band for Mrk 501 (Kataoka et al. 1999), the source was displaying a harder-when-brighter trend during this campaign. This has also been observed in the past for Mrk 421 (Takahashi et al. 1990).

3. BROADBAND OBSERVATIONS

3.1. Very-High-Energy Gamma Rays

3.1.1. MAGIC

MAGIC is a VHE instrument composed of two imaging atmospheric Cherenkov telescopes (IACTs) with mirror diameters of 17 m, located at 2200 m above sea level at the Roque de Los Muchachos Observatory on La Palma, Canary Islands, Spain. The energy threshold of the system is 50 GeV and it reaches an integral sensitivity of 0.66% of the Crab Nebula flux above 220 GeV with a 50-hour observation (Aleksić et al. 2015a).

MAGIC observed Mrk 501 in 2013 from April 9 (MJD 56391) to August 10 (MJD 56514). On July 11 (MJD 56484), ToO observations were triggered by the high count rate of $\sim$15 counts s$^{-1}$ observed by Swift XRT (see Section 3.3). The flaring state was observed intensively for five consecutive nights until July 15 (MJD 56488). After that the observations continued with a lower cadence until August 10.

The source was observed during 17 nights, collecting a total of 22 hours of data with zenith angles between 10$^\circ$ and 60$^\circ$. Only five hours survived the standard quality cuts for regular MAGIC data analysis because many observations were taken during the presence of a Saharan sand-dust layer in the atmosphere known as “Calima”. As we explain below, using the LIDAR information we could recover 10 of the 17 hours which would have been
of one day, which is a typical feature of a Calima layer (unlike a cloudy sky). The precision on the energy correction is estimated to be around 5% of the attenuation (40% to 15%), which corresponds to < 2% of the estimated energy, at most. After the Calima correction, the energy threshold increases inversely proportional to the transmission value. This correction method was tested independently on a Crab Nebula dataset observed under similarly hazy weather conditions (Fruck & Gaug 2015). Details of the method can be found in Fruck (2014). This is the first time an event-by-event atmospheric correction is applied to MAGIC data.

The analysis results of the MAGIC data taken during good weather conditions have a systematic uncertainty in the flux normalization and in the energy scale. For both of them, the component changing run-by-run is estimated to be ~11% using Crab Nebula observations (Aleksic et al. 2015a). It is attributed mainly to the atmospheric transmission of the Cherenkov light, which can change on a daily basis (even during so-called good weather conditions) and the mirror reflectivity, which can change also on a daily basis due to the deposition of dust. The atmospheric correction applied in the analysis of the data taken during Calima increases this run-by-run systematic error from 11% to 15% due to the uncertainty in the correction. Since the systematic uncertainty can be different according to the atmospheric correction, we have added 15% or 11% (with or without the atmospheric correction) to the statistical errors of the flux in quadrature for the evaluation of flux variability.

The summary of the MAGIC analysis results for observations occurring simultaneously with NuSTAR is provided in Table 3. The derived spectra are shown in Figure 4, where the spectral points are drawn with statistical (1σ) error bars shown for each of the spectral points.

Figure 4. MAGIC and VERITAS spectra averaged over epochs with simultaneous NuSTAR exposures. The power-law spectral fitting parameters for the VHE data are summarized in Table 3. Only statistical (1σ) error bars are shown for each of the spectral points.

All the data were analyzed following the standard procedure (Aleksić et al. 2012) using the MAGIC Analysis and Reconstruction Software (MARS; Zanin et al. 2013). An image cleaning was applied based on information of signal amplitude and timing of each pixel, and the shower images were parametrized using the Hillas parameters (Hillas 1985). For the reconstruction of the gamma-ray direction and the gamma-hadron separation, the random forest method is applied using the image parameters and the stereoscopic parameters. (Albert et al. 2008; Aleksic et al. 2010). The energy reconstruction utilizes look-up tables. The analysis steps were confirmed independently with data from the Crab Nebula and dedicated Monte Carlo simulations of gamma-ray showers.

A fraction of the dataset (10.4 of 15.1 hours, specifically the observations between MJD 56485 and MJD 56514) was affected by “Calima,” a Saharan sand-dust layer in the atmosphere. A correction within the framework of the MARS software is applied to account for the absorption due to Calima using LIDAR measurements taken simultaneously with the MAGIC observations (Fruck et al. 2013). The correction was carried out in two steps. Due to the dust attenuation during Calima, the estimated energy is shifted towards low energies, and thus is corrected event by event, as the first step. Then, to account for the shift of the energy estimation, a correction to the collection area is applied as a second step, due to the energy dependence in the collection area. The atmospheric transmission values for this method were obtained from the temporally closest LIDAR measurement. During the observations affected by Calima the atmospheric transmission ranged from 85% down to 60%, being relatively stable within a timescale.
The VERITAS observations were taken with 0.5◦ offsets in each of the four cardinal directions to enable simultaneous background estimation [Fomin et al. 1993]. Events were reconstructed following the procedure outlined in Acciari et al. [2008a]. The recorded shower images were parameterized by their principal moments, giving an efficient suppression of the far more abundant cosmic-ray background. Cuts were applied to the mean scaled width, mean scaled length, apparent altitude of the maximum Cherenkov emission (shower maximum), and the angular distance between the position of Mrk 501 and the reconstructed origin of the event. The results were independently reproduced with two analysis packages [Cogan 2008, Prokopf 2013]. The uncertainty on the energy calibration of VERITAS is estimated at 20%. Additionally, the systematic uncertainty on the spectral index is estimated at 0.2, appearing to be relatively independent of the source slope [Madhavan 2013].

A differential power law is fit to the data (dN/dE ∝ E−α) to characterize the VHE spectrum of the source. VERITAS observed Mrk 501 to vary by no more than a factor of three in flux throughout the observations, with the integral flux ranging from (1.85 ± 0.38) × 10−11 ph cm−2s−1 above 200 GeV (8% Crab Nebula flux above the same threshold) on MJD 56395 to (4.45 ± 0.61) × 10−11 ph cm−2s−1 (20% Crab Nebula flux) on MJD 56421. The source displayed low spectral variability, ranging between Γ = 3.1 ± 0.4 in the low flux state to Γ = 2.19 ± 0.07 in the higher flux state. The observation and analysis results are summarized in Table 3 (for NuSTAR simultaneous observations only), with the VHE spectra of the NuSTAR simultaneous observations shown in Figure 4. Day-to-day uncertainties in flux calculations that might be introduced by different atmospheric conditions (even under strictly good weather conditions) are not included in Table 3 and are estimated at less than 10%.

3.1.3. VHE Results

MAGIC and VERITAS observations, analysis and spectral fit summary for NuSTAR-simultaneous observations. Observations occurring on the same day are grouped with horizontal lines. Daily average values of MAGIC observations are shown in bold, below the results for each observation occurring on that day. Statistical (1σ) error bars are provided for the power-law indices and the integral fluxes. The flux value between MJD 56412 to MJD 56414 (shown in italics) is estimated with fitting parameters due to an energy threshold above 200 GeV.

The significance of the observed gamma-ray signals is computed according to Eqn. 17 in [Li & Ma 1983].

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<tr>
<td>56486.966</td>
<td>56487.091</td>
<td>2.2</td>
<td>MAGIC</td>
<td>30-40</td>
<td>31.8</td>
<td>2.31±0.05</td>
<td>20.9±0.7</td>
<td>30.4</td>
<td>12</td>
</tr>
</tbody>
</table>

The full light curve of VHE observations from MAGIC and VERITAS is shown in Figure 5, with a zoom into the period of elevated flux in Figure 6. The flux values are shown with statistical errors only. The MAGIC and VERITAS observations of Mrk 501 in 2013 show the state in states which are consistent with the range of states observed in the past. The observations of VERITAS, occurring primarily in the beginning of the campaign, detected the source in a 5-10% Crab state, in agreement with the early MAGIC observations. Later on in the campaign, MAGIC observed a flux elevated state of order ~2.5 times the Crab flux.

3.2. High-Energy Gamma Rays

Fermi LAT is a pair-conversion telescope sensitive to photons between 30 MeV and several hundred GeV [Atwood et al. 2009]. Spectral analysis was completed for two periods contemporaneous with the NuSTAR observations using the unbinned maximum-likelihood method implemented in the LAT ScienceTools software package version v9r31p1, which is available from the Fermi Science Support Center. The LAT data between MJD 56381 and MJD 56424 was used for comparison with the first two NuSTAR exposures, while MJD 56471 to MJD 56499 was used for NuSTAR exposures occurring during the elevated state.

“Source” class events with energies above 100 MeV within a 12◦ radius of Mrk 501 with zenith angles < 100◦ and detected while the spacecraft was at a < 52◦ rocking angle were used for this analysis. All sources within the region of interest from the second Fermi LAT catalog (2FGL [Nolan et al. 2012]) are included in the model. With indices held fixed, the normalizations of the component were allowed to vary freely during the spectral fitting, which was performed using the instrument response functions P7REP_SOURCE_V15. The Galactic diffuse emission and an isotropic component, which is the sum of the extragalactic diffuse gamma-ray emission and the residual charged particle background, were modeled using the recommended files. The flux values were computed us-

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furnissetal
Figure 5. The broadband light curves of Mrk 501 from MJD 56380 to 56520. The VHE data are shown with statistical error bars only. Optical data are corrected as described in Section 3.4. All radio light curve points for 2-110mm are provided by the F-Gamma consortium.

During the first epoch (MJD 56381–56424), the spectral analysis of the LAT data shows the blazar had an integral flux of $F_{0.1-100\text{GeV}} = (5.3 \pm 4.4) \times 10^{-8}$ ph cm$^{-2}$ s$^{-1}$, and an index of $\Gamma = 2.0 \pm 0.3$. Analysis of the second epoch (MJD 56471–56499) results in an integral flux of $F_{0.1-100\text{GeV}} = (6.5 \pm 2.1) \times 10^{-8}$ ph cm$^{-2}$ s$^{-1}$ and index of $\Gamma = 1.7 \pm 0.1$. These values are consistent with the average flux and index values calculated over the first 24 months of the science phase of the LAT mission and reported in the 2FGL catalog ($F_{0.1-100\text{GeV}} = (4.8 \pm 1.9) \times 10^{-8}$ ph cm$^{-2}$ s$^{-1}$ and $\Gamma = 1.74 \pm 0.03$; Nolan et al. 2012).
3.3. **Swift X-Ray and UV Telescope Observations**

The XRT onboard *Swift* ([Gehrels et al.](https://doi.org/10.1051/0004-6361:20031435)) is a focusing X-ray telescope sensitive to photons with energies between 0.3 and 10 keV. The *Swift* satellite observed Mrk 501 59 times between 2013 January 1 and 2013 September 5 (MJD 56293 to 56540). All XRT observations were carried out using the Windowed Timing (WT) readout mode. The data set was first processed with the XRT-DAS software package (v.2.9.0) developed at the ASI Science Data Center and distributed by HEASARC within the HEASoft package (v. 6.13). Event files were calibrated and cleaned with standard filtering criteria with the *xrtpipeline* task using the calibration files as available in the *Swift* CALDB version 20140120.

The spectrum from each observation was extracted from the summed and cleaned event file. Events for the spectral analysis were selected within a circle of 20 pixel (~46") radius, which encloses about 80% of the *Swift* XRT point spread function (PSF), centered on the source position. The background was extracted from a nearby circular region of 40 pixel radius. The ancillary response files were generated with the *xrtmkarf* task, applying corrections for PSF losses and CCD defects using the cumulative exposure map. The latest response matrices (v.014) available in the *Swift* CALDB were used.

Before the spectral fitting, the 0.3-10 keV source energy spectra were binned to ensure a minimum of 20 counts per bin.

The data were fit with an absorbed power-law model, with index $\Gamma$, as well as an absorbed log-parabolic model, where in both cases the neutral hydrogen column density was set at $1.55 \times 10^{20}$ cm$^{-2}$, taken from [Kalberla et al.](https://doi.org/10.1051/0004-6361:20054161). The summary of the XRT observations and spec-
analysis results are provided in Table 4. The light curve of the observations, including 0.3-3 keV and 3-7 keV integral flux bands, is shown in Figure 5, with a zoom into the period of elevated flux in Figure 6. The 3-7 keV band is not traditionally quoted for Swift XRT data, but is motivated by direct comparison to the 3-7 keV band computed for the NuSTAR observations.

Mrk 501 displays a relatively steady flux state until after MJD 56480, when the flux increases to $38.3\pm1.5 \times 10^{-11}$ ergs cm$^{-2}$ s$^{-1}$ on MJD 56483 (corresponding to the day with the XRT count rate of 15 counts s$^{-1}$ which triggered MAGIC and NuSTAR observations). This high X-ray state was followed by a general drop in flux, continuing through the last XRT observation included in this work (2013 September 1; MJD 56540).

The power-law fitted indices and 3-7 keV flux derived from the power-law fits are plotted in Figure 7 for all 59 observations. The source clearly displays the variability was detected to occur within single exposures due to different filter spectral responses and analysis procedures of the various optical data sets (e.g. for signal and background extraction) in combination with the strong host galaxy contribution (~12 mJy for an aperture of 7.5″ in the R-band), the reported fluxes required instrument-specific offsets of a few mJy. These offsets are introduced in order to align multi-instrumental light curves, and were determined using several of the GASP-WEBT instruments as reference, and scaling the other instruments using simultaneous observations. The required offsets for each instrument are as follows: Abastumani (70cm)=4.8 mJy; Skinakas=1.2 mJy; Rozhen (60cm)=1.3 mJy; Vidoejeva (60cm)=2.2 mJy; St.Petersburg=0.3 mJy; Perkins=0.6 mJy; Liverpool=0.6 mJy; AAVSOnet=−3.4 mJy; WMO=−0.7 mJy; TUG T60=−0.5 mJy; TUG T100=−1.2 mJy. Additionally, a point-wise fluctuation of 0.2 mJy (~0.01mag) was added in quadrature to the statistical errors in order to account for potential differences of day-to-day observations within single instruments. Within Figure 5, the R-band observations can be seen to remain fairly steady around 4.5 mJy.

3.5. Radio
3.5.1. Metsähovi

The 14-m Metsähovi Radio Observatory also participated in this multi-instrument campaign, as it has been doing since 2008. Metsähovi observed Mrk 501 every few days at 37 GHz. Details of the observing strategy and data reduction can be found at [Teräsranta et al. (1998)].
As can be seen in the bottom panel of Figure 5, there is evidence of a low level of variability at 37 GHz as observed by Metsähovi. This variability is quantified in terms of fractional variability (see Section 5.1).

3.5.2. OVRO

Regular 15 GHz observations of Mrk 501 were carried out using the OVRO 40-m telescope with a nominal bi-weekly cadence (Richards et al. 2011). The instrument consists of off-axis dual-beam optics and a cryogenic high electron mobility transistor low-noise amplifier with a 15 GHz center frequency and 3 GHz bandwidth. The two sky beams were Dicke-switched using the off-source beam as a reference, while the source was alternated between the two beams in an ON-ON mode to remove atmospheric and ground contamination. The total system noise temperature was about 52 K. The typical noise level achieved in a 70-second observation was 3–4 mJy. The noise temperature was about 52 K. The typical noise level achieved in a 70-second observation was 3–4 mJy. The noise level is due to pointing errors, but does not include the systematic uncertainty in absolute calibration of about 5%. Calibration was performed using a temperature-stable diode noise source to remove receiver gain drifts; the flux density scale is derived from observations of 3C 286 assuming the Baars et al. (1977) value of 3.44 Jy at 15 GHz. Details of the reduction and calibration procedure can be found in Richards et al. (2011).

3.5.3. F-Gamma

The cm/mm radio light curves of Mrk 501 were obtained within the framework of a Fermi-related monitoring program of gamma-ray blazars (F-Gamma program; Fuhrmann et al. 2007; Angelakis et al. 2008). The millimeter observations were closely coordinated with the more general flux monitoring conducted by IRAM, and data from both programs are included here. The overall frequency range spans from 2.64 GHz to 142 GHz using the Effelsberg 100-m and IRAM 30-m telescopes.

The Effelsberg measurements were conducted with the secondary focus heterodyne receivers at 2.64, 4.85, 8.35, 10.45, 14.60, 23.05, 32.00 and 43.00 GHz. The observations were performed quasi-simultaneously with cross-scans; that is, slewing over the source position, in azimuth and elevation direction with an adaptive number of sub-scans for reaching the desired sensitivity (for details, see Fuhrmann et al. 2008; Angelakis et al. 2008). Subsequently, pointing offset correction, gain correction, atmospheric opacity correction and sensitivity correction were applied to the data.

The IRAM 30-m observations were carried out with calibrated cross-scans using the Eight MXer Receiver (EMIR) horizontal and vertical polarization receivers operating at 86.2 and 142.3 GHz. The opacity-corrected intensities were converted to the standard temperature scale and finally corrected for small remaining pointing offsets and systematic gain-elevation effects. The conversion to the standard flux density scale was done using the instantaneous conversion factors derived from frequently observed primary (Mars, Uranus) and secondary (W3(OH), K3-50A, NGC 7027) calibrators.

4. SIMULTANEOUS NuSTAR AND SWIFT EXPOSURES

Since Mrk 501 is highly variable, detailed inferences regarding the broadband SED and its temporal evolution require simultaneous observations of multiple bands. In particular, for the determination of the low-energy peak $E_{\text{syn}}$, and the flux at $E_{\text{syn}}$, $F(E_{\text{syn}})$, Swift XRT and NuSTAR observations must be simultaneous. There are five periods within the campaign for Mrk 501 where the observations by NuSTAR and Swift occurred within one hour of each other. The Swift exposure IDs for these quasi-simultaneous periods are summarized in Table 4. For Mrk 501, $F(E_{\text{syn}})$ is located in the X-ray band and can be determined reliably (except for the first NuSTAR observation where $E_{\text{syn}}$ is $\leq 0.85$ keV) since there is no evidence of X-ray variability of Mrk 501 on a time scale shorter than a NuSTAR orbit (~ 90 minutes).

As a precursor to the joint fitting of XRT and NuSTAR data, we confirm agreement between the 3-7 keV flux values derived from the Swift XRT and NuSTAR fitted models. There is a residual discrepancy (not a uniform offset) at the level of $< 10\%$. Using XSPEC, we performed simultaneous fitting to the datasets using the absorbed log-parabolic model as done in Section 2 for the NuSTAR data alone. During the fitting process, we allowed the normalizations of the data sets to vary, but required the same spectral shape parameters. A representative plot of the simultaneous fit for XRT and NuSTAR data collected on MJD 56485 is provided in Figure 8. The model spectrum is shown as a solid line in Figure 8. The agreement between XRT and NuSTAR was studied and found to be within the calibration uncertainties.

For the determination of the spectral parameters characterizing the synchrotron peak (namely the energy $E_{\text{syn}}$ and $F(E_{\text{syn}})$) with the simultaneous NuSTAR and Swift

\begin{table}[ht]
\centering
\begin{tabular}{cccccccc}
\hline
Observation & Date & Exp & Flux & Flux & Flux & Index & $\chi^2$/DOF \\
ID & [MJD] & [s] & 2-10 keV & 0.5-2 keV & 3-7 keV & 0.3-3 keV & \hline
00080176001 & 56395.06 & 9636.0 & 6.9±0.1 & 6.4±0.06 & 3.6±0.1 & 11.0±0.1 & 2.05±0.01 \& 403.5/416 & 2.06±0.02 & -0.02±0.04 \& 402.6/415 \\
00091745001 & 56485.98 & 709.1 & 21.1±1.7 & 12.7±0.4 & 9.1±0.9 & 22.3±0.7 & 1.77±0.05 \& 108.1/94 & 1.74±0.08 & 0.10±0.16 \& 107.0/93 \\
00030793235 & 56485.98 & 709.1 & 14.6±0.2 & 13.1±0.9 & 24.1±0.4 & 1.73±0.03 \& 282.7/222 & 1.73±0.05 & 0.03±0.09 \& 227.6/221 \\
00030793236 & 56486.31 & 1002.0 & 24.9±0.7 & 14.1±0.3 & 13.4±0.6 & 23.4±0.4 & 1.73±0.03 \& 291.6/270 & 1.68±0.04 & 0.13±0.08 \& 265.1/260 \\
00030793237 & 56487.04 & 949.5 & 19.1±0.9 & 12.0±0.2 & 10.4±0.4 & 18.9±0.3 & 1.76±0.03 \& 229.9/237 & 1.73±0.05 & 0.07±0.08 \& 228.9/236 \\
\hline
\end{tabular}
\end{table}
XRT observations, we apply the log-parabolic model modified by the photoelectric absorption due to our Galaxy, with a (fixed) neutral hydrogen column density of $1.55 \times 10^{20} \text{ cm}^{-2}$, taken from Kalberla et al. (2005). The procedure to search for $E_{\text{syn}}$ involves the variation of the “normalization energy” parameter (in the logpar model in XSPEC) until the local index $\Gamma$ returns a value of 2 — then $E_{\text{syn}}$ corresponds to the peak in the $E \times F(E)$ representation. This procedure correctly accounts for the effect of the soft X-ray absorption by Galactic column density as the absorption is included in the model fitted to the data. For the determination of the error on $E_{\text{syn}}$, we freeze the “local index” — defined at energy $E_{\text{syn}}$ — to a value of 2, and then step the value of $E_{\text{syn}}$ keeping all other parameters free. We then search for the value of the $E'_{\text{syn}}$ which corresponds to the departure of $\chi^2$ from the minimum by $\Delta \chi^2 = 2.7$. The error quoted is the difference between $E_{\text{syn}}$ and $E'_{\text{syn}}$. The $E_{\text{syn}}$ and curvature parameters ($\beta$) for each of the simultaneous data sets are summarized in Table 5. We quote the value of $F(E_{\text{syn}})$ inferred from the NuSTAR module FPMA (Focal Plane Module A).

The combination of Swift XRT and NuSTAR observations provides an unprecedented view of the synchrotron peak variability. From Table 5, it is evident that the synchrotron peak moves by a factor of about ten during this campaign, with the highest synchrotron peak occurring during the elevated X-ray and gamma-ray state.

5. VARIABILITY

5.1. Fractional Variability

In order to quantify the broadband variations we utilize the fractional variability, $F_{\text{var}}$. We follow the description given in Vaughan et al. (2003), where $F_{\text{var}}$ is calculated as:

$$F_{\text{var}} = \sqrt{\frac{S^2 - \langle \sigma^2 \rangle}{\langle F_\gamma \rangle^2}}$$

where $\langle F_\gamma \rangle$ is the average photon flux, $S$ is the standard deviation of the flux measurements, and $\langle \sigma^2 \rangle$ is the mean squared error of the measurement.

$F_{\text{var}}$ was determined for the temporal binning and sampling presented in Figure 5 and Table 3 (for MJD 56485 and 56486, the bold lines in Table 3 are used). The value of $F_{\text{var}}$ is known to be dependent on sampling and should be interpreted with caution. For example, a well sampled light curve with small temporal bins will allow us to

Figure 8. Example of a broadband X-ray spectrum of Mrk 501 in the crucial region where the synchrotron peak (in the $E \times F(E)$ representation) is located. The spectra result from a simultaneous observation with Swift (green) and NuSTAR (FPMA: red, FPMB: black) on 2013 July 12-13. The spectral fit used a log-parabolic model (see the text) with Galactic column density of $1.55 \times 10^{20} \text{ cm}^{-2}$. For the purpose of illustrating the intrinsic spectrum of the source, the solid lines which represent the fit to the Swift and NuSTAR data show the spectrum before the Galactic absorption. The normalizations of the Swift and NuSTAR data were allowed to be free, and the offset between them was less than 10%, thus illustrating generally good cross-calibration of the two instruments.
Fitting results for Swift XRT and NuSTAR simultaneous observations. The data were simultaneously fit with a log-parabolic function.

<table>
<thead>
<tr>
<th>Observation ID</th>
<th>Date [MJD]</th>
<th>Orbit Number</th>
<th>$E_{\text{syn}}$ [keV]</th>
<th>$F(E_{\text{syn}}) \times 10^{-11}$ ergs cm$^{-2}$s$^{-1}$</th>
<th>Curvature $\beta$</th>
<th>$\chi^2$/DOF</th>
</tr>
</thead>
<tbody>
<tr>
<td>60002024002</td>
<td>56395.1</td>
<td>1</td>
<td>&lt;0.85</td>
<td>4.1</td>
<td>0.061</td>
<td>669/673</td>
</tr>
<tr>
<td>60002024006</td>
<td>56485.9</td>
<td>1</td>
<td>4.9±0.7</td>
<td>13.8</td>
<td>0.21</td>
<td>596/577</td>
</tr>
<tr>
<td>60002024006</td>
<td>56486.0</td>
<td>2</td>
<td>5.1±0.9</td>
<td>13.7</td>
<td>0.22</td>
<td>697/715</td>
</tr>
<tr>
<td>60002024006</td>
<td>56486.2</td>
<td>4</td>
<td>7.0±0.8</td>
<td>14.6</td>
<td>0.2</td>
<td>877/848</td>
</tr>
<tr>
<td>60002024008</td>
<td>56487.1</td>
<td>4</td>
<td>3.3±0.9</td>
<td>11.2</td>
<td>0.17</td>
<td>832/851</td>
</tr>
</tbody>
</table>

![Figure 9](image-url)  
Figure 9. The fractional variability ($F_{\text{var}}$) calculated for each instrument separately.

probe the variability on small timescales (e.g. NuSTAR), which could be hidden if the variability is computed with fluxes obtained with relatively coarse temporal bins (e.g. Fermi LAT).

The fractional variability for each band (from 15 GHz radio through VHE) is shown in Figure 9. For the period of observations covered in this work, the fractional variability shows a double-peaked shape with the highest variability in the X-ray and VHE bands. A similar broadband variability pattern has recently been reported for Mrk 501 (Doert 2013; Aleksić et al. 2015c), for Mrk 421 (Aleksić et al. 2015b; Baloković et al. 2013) and for other high-synchrotron-peaked blazars in, for example, Aleksić et al. (2014). This double-peaked shape of $F_{\text{var}}$ from radio through VHE can be interpreted as resulting from a correlation between the synchrotron and inverse-Compton peaks.

$F_{\text{var}}$ is below ~5% at 15 GHz and optical/UV frequencies, while at 37 GHz the fractional variability is ~20%. The relatively high fractional variability at 37 GHz is not produced by any single flaring event, but rather by a consistent flickering in the radio flux. Such flickering is not typically observed in blazars, but has been reported for Mrk 501 in Aleksić et al. (2015d). At X-ray frequencies, $F_{\text{var}}$ gradually increases with energy, reaching the largest value (~0.6) in the 7-30 keV band measured by NuSTAR. The $F_{\text{var}}$ computed for the Swift XRT 3-7 keV observations is higher than for the NuSTAR 3-7 keV fluxes due to the larger temporal coverage of the Swift observations, allowing for observation of Mrk 501 during high activity levels that were not observed with NuSTAR.

The Swift XRT $F_{\text{var}}$ for Mrk 501 published in Stroh & Falcone (2013) was 0.15 or 0.18, depending on the timescale used for calculation, illustrating that the value of $F_{\text{var}}$ is dependent on sampling. In Abdo et al. (2011a), RXTE-ASM (2-10 keV) and Swift BAT (15-50 keV) show $F_{\text{var}}$ values between 0.2 and 0.3, although it should be noted that due to the limited sensitivity of RXTE-ASM and Swift BAT (in comparison with Swift XRT and NuSTAR), the variability was studied on timescales larger than 30 days.

5.2. Cross Correlations

Cross-correlations between the different energy bands were studied with the Discrete Correlation Function (DCF) described in Edelson & Krolik (1988). The DCF method can be applied to unevenly sampled data, and no interpolation of the data points is necessary. Also, the errors in the individual flux measurements are naturally taken into account when calculating the DCF. One important caveat, however, is that the resulting DCF versus time lag relation is not continuous, and hence the results should only be interpreted with a reasonable balance between the time resolution and the accuracy of the DCF values. It is also important to only consider instruments with similar time coverage. In this study, we considered all the energy bands with a non-zero fractional variability. Among the Swift UVOT data, only the UVW2 filter was checked, as it is the filter which has the best time coverage across the Swift UVOT observations and also is least contaminated by the host galaxy light. For a better time coverage, MAGIC and VERITAS data points are combined to make a single data set as the VHE band.

A significant correlation in the DCF was seen only between the VHE data and the 0.3-3 keV and the 3-7 keV Swift XRT bands. For both of the combinations, the largest correlation is seen with a time lag of 0±1.5 days. This result does not change if the binning of 3 days is altered. Note that the NuSTAR observations covered a relatively short period with a dense sampling, thus we did not see any significant correlation between NuSTAR and any other band. Since the observations of Swift XRT and NuSTAR were made simultaneously (within a few hours) with the VHE observations, correlations between the X-ray and the VHE observations were investigated in more detail (see Section 5.3). R

5.3. X-ray/VHE Correlation

The light curve of the broadband observations is shown in Figure 5, with a zoom of the period showing an elevated X-ray and VHE state in Figure 6. The VERITAS and MAGIC flux points within the light curve are shown with statistical errors only. Correlation studies using the VHE flux values are completed with statistical and systematic errors included, as described below. The radio,
optical and UV observations show relatively steady flux over the campaign period, while the largest amplitude of variability can be seen in the X-ray and VHE gamma-ray bands. An elevated state in both the X-ray and VHE bands can be seen to occur on MJD 56483 (Swift Observation ID 00030793232 in Table 4). Zooming in on this epoch (Figure 6), shows that the NuSTAR observations occurring on MJD 56485 and 56486 occurred after the highest state observed by MAGIC and Swift. The XRT observations show an elevated X-ray flux in both the 0.3-3 and 3-7 keV bands on MJD 56483.

A comparison between the NuSTAR-observed X-ray photon flux values (derived from XSPEC) in the 3-7 and 7-30 keV bands and the epochs of simultaneous VHE observations is shown in Figure 10. During this campaign, 10 observations occurred within one hour between either NuSTAR and MAGIC (7 observations) or NuSTAR and VERITAS (3 observations). The simultaneous X-ray and VHE data, where the VHE data include both statistical and systematic errors, were fit with both a linear and a quadratic function.

Within the one-zone SSC emission paradigm, there is a physical motivation for a quadratic relationship between the X-ray and VHE flux values (Marscher & Gear 1985). More specifically, the inverse-Compton flux depends not only on the density of photons, but also on the density of the electron population producing those photons. If, however, the particle population is energetic enough for the inverse-Compton scattering to occur in the Klein-Nishina regime, the relationship between the X-ray and VHE fluxes can be complex and will depend in detail on the energy bands considered, the particle energy loss mechanisms and the magnetic field evolution. In particular, Katarzyński (2005) suggest that a roughly linear relationship may arise during the declining part of a flare when the emitting region expands adiabatically, leading to a decrease of both the particle number density and the magnetic field strength.

A quadratic relationship provides a better fit than the linear fit for the 3-7 keV flux values measured simultaneously by NuSTAR, with $\chi^2$ of 11.4 and 87.3, respectively, for 9 DOF. The 3-7 keV flux and the > 200 GeV flux are highly correlated, with a Pearson correlation coefficient ($r$) of 0.958. For the 3-7 keV band, the quadratic function fits the data better than the linear function, with $\chi^2$ of 58.0 and 114.0, respectively, for 11 DOF. The $r$-value for the 3-7 keV flux as measured with Swift and the > 200 GeV flux is 0.954.

6. MODELING THE BROADBAND SPECTRAL ENERGY DISTRIBUTION

Previous MWL campaigns on Mrk 501 have been sufficiently characterized with a one-zone SSC model (Acciari et al. 2011; Abdo et al. 2011a), although there are a few notable instances where a one-zone SSC model was found not to be appropriate for the broadband emission (Pian et al. 1998; Kataoka et al. 1999). In this study we decided to use the simplest approach, which is provided by a leptonic model with a single emitting region. The broadband spectral data were modeled with an equilibrium version of the single-zone SSC model from Böttcher & Chiang (2002) and Böttcher et al. (2013). This model has been used to describe the broadband emission from various other VHE-detected blazars (e.g. Acciari et al. 2009a; Abdo et al. 2011b; Alu et al. 2011, 2013).

Within this equilibrium model, the emission originates from a spherical region of relativistic leptons with radius $R$. This emission region moves down the jet with a Lorentz factor $\Gamma$. We set the Doppler factor $\delta$ to 15 for all model representations. Notably, it has been shown that when using least-squares fitting of emission models to broadband data of Mrk 501, the Doppler factor can vary widely from state to state (Mankuzhiyil 2012). We do not complete least-squares fitting in this work and instead choose to fix the Doppler factor to 15 for the representation of all states, limiting the number of free parameters of the SSC model. The Doppler factor of 15 is similar to the Doppler factor used in previous studies of Mrk 501 (Acciari et al. 2011; Abdo et al. 2011a; Mankuzhiyil 2012). In order to reduce the number of free parameters, the jet axis is aligned toward the line of sight with the critical angle $\theta = 3.8^\circ$. At the critical angle, the jet Lorentz factor is equal to the Doppler factor ($\Gamma = \delta$).

Within this emission model, relativistic leptons are injected into this emission region continuously according to a power-law distribution $Q = Q_0 \gamma^{-q}$ between $\gamma_{\text{min}}$ and $\gamma_{\text{max}}$. The injected population of particles is allowed to cool. The simulation accounts for synchrotron emission due to a tangled magnetic field $B_0$, Compton up-scattering of synchrotron photons, $\gamma \gamma$ absorption and the corresponding pair production rates (via the general solution in Böttcher & Schlickeiser 1997). The cooling of the injected electrons is dominated by radiative losses, which are balanced by injection and particle escape from the system. This particle escape is characterized with an escape efficiency factor $\eta = 100$, where $\tau_{\text{esc}} = \eta R/c$. The use of $\eta = 100$ is motivated by success in representing SEDs of TeV blazars in previous studies using the same model (e.g. Alu et al. 2013). The electron cooling rates and photon emissivity and opacity are calculated using similar routines of the code for jet radiation transfer described in Böttcher et al. (1997). Together, the particle injection, cooling and escape mechanisms lead to an equilibrium particle population.
Figure 10. *NuSTAR* X-ray photon flux versus simultaneous $>200$ GeV flux from MAGIC and VERITAS. The dotted lines show quadratic fits to the data, while the dashed lines show linear fits to the 3-7 keV and 7-30 keV bands.

Figure 11. *Swift* 0.3-3 and 3-7 keV X-ray photon flux values versus simultaneously measured $>200$ GeV flux from MAGIC and VERITAS. The black and blue dotted lines show quadratic fits to the 3-7 keV and 0.3-3 keV data, respectively, while the black and blue dashed lines show linear fits to the 0.3-3 keV and 3-7 keV bands, respectively. For completeness, we also compare the linear and quadratic fits of the simultaneous 3-7 keV *NuSTAR* and $>200$ GeV flux from MAGIC and VERITAS summarized in Figure 10 (light grey dashed and dotted line).
A key result of the equilibrium that occurs between continual particle injection, particle escape and radiative cooling is a break in the electron distribution, \( \gamma_b \) (referred to as \( \gamma_c \) within Böttcher et al. \( 2013 \)), where \( t_{\text{esc}} = t_{\text{cool}}(\gamma_b) \). As described in Equations (1) and (2) of Böttcher et al. \( 2013 \), if \( \gamma_b \) is smaller than \( \gamma_{\text{min}} \), and an index of \((q+1)\) for Lorentz factors above \( \gamma_{\text{min}} \). In the slow cooling regime, the resulting broken power law of the equilibrium particle distribution is equal to the injected spectrum \((q)\) for particles with Lorentz factor below \( \gamma_b \), and \((q+1)\) above \( \gamma_b \). It is known that a hard injected electron spectrum would lead to a small amount of pile-up, followed by a smooth cut-off toward the high-energy end of the distribution (for details, see, e.g. Kardeshev \( 1962 \) and Stawarz et al. \( 2008 \)). More specifically, the equilibrium electron spectrum slightly deviates from the \((q+1)\) approximation at the high-energy end \((\gamma \sim \gamma_{\text{max}})\) due to pile-up effects that increase as the injected spectrum becomes harder (i.e. \( q < 1.5 \)). Notably, although scattering in the KN regime is appropriately accounted for within the SSC model, neither the pile-up at the highest energy nor the energy loss (Compton cooling) of the electrons participating in scattering within the KN regime is accounted for within the model. The two aforementioned effects, however, are expected to result in a negligible deviation of the equilibrium electron spectrum from the approximated index of \( q+1 \).

\( L_e \) is the kinetic power in the relativistic electrons and \( L_B \) is the power in the Poynting flux carried by the magnetic field of the equilibrium particle distribution. The \( L_e \) and \( L_B \) parameters allow the calculation of the equipartition parameter \( L_B/L_e \). A state with an equipartition near unity minimizes the total magnetic field + particle energy requirement to produce a given synchrotron flux. Therefore, from an energetics point of view a situation near equipartition is usually favored. If the jet is powered by a Blandford-Znajek type mechanism, it is expected to be initially Poynting-flux dominated, and this luminosity is then (through an unknown mechanism, possibly magnetic reconnection) converted partially into particle energy. This conversion is expected to stop at an approximately equipartition situation as an equilibrium is reached between the conversion of magnetic energy to particle energy, and vice versa (via turbulent charged-particle motion generating small-scale, turbulent magnetic fields). For examples of blazar modeling based on equipartition, see Cerruti et al. \( 2013 \); Dermer et al. \( 2014 \). Alternatively, a sub-equipartition magnetic field may be expected in an MHD-driven, initially particle-dominated jet, where magnetic fields could be self-generated (amplified) by, e.g., shocks. The sub-equipartition magnetic fields that are often found in blazar SED modeling might therefore favor this latter scenario. Sub-equipartition states are a common result in the application of single-zone SSC emission scenarios to VHE blazars, as in Aliu et al. \( 2012a \); Acciari et al. \( 2009b \); \( 2008b \); and Abdo et al. \( 2011 \).

The broadband data and model representations for five days from the MWL observation campaign are shown in Figure 12. The flux resulting from the model simulation (solid line) is corrected for absorption by interaction with the extragalactic background light (EBL) for the redshift of \( z = 0.03 \), assuming the EBL model outlined in Domínguez et al. \( 2011 \). The model thus represents the observed VHE emission as opposed to the intrinsic VHE emission. When applying the model to the data, the radio flux is likely to include a significant portion of extended radio emission and is therefore taken as an upper limit, as done in Abdo et al. \( 2011a \).

The parameters used to represent the data with the equilibrium model are summarized in Table 6. The data in this work are represented with the emission model within the fast cooling regime, where the emitting equilibrium particle population follows \( n(e) \propto \gamma^{-2} \) for \( \gamma_b < \gamma < \gamma_{\text{min}} \) and \( n(e) \propto \gamma^{-(q+1)} \) for \( \gamma_{\text{min}} < \gamma < \gamma_{\text{max}} \). A particle population with an injection index of \( q = 1.8 - 1.9 \) provides a reasonable representation of the synchrotron emission on MJD 56395 (red; top panel) and 56420 (green; second panel from top). There are no Swift data for observations on MJD 56420. Each of these epochs (MJD 56395 and 56420) can be sufficiently described with similar parameters, although theSED on MJD 56420 requires a slightly more energetic electron population and lower magnetic field to account for the marginally elevated X-ray and VHE emission as compared to what is observed on MJD 56395.

Although the highest VHE gamma-ray (\( \geq 200 \) GeV) flux during this campaign was observed by MAGIC on MJD 56484, a reliable spectrum from that MAGIC observation could not be reconstructed due to the presence of Calima and the lack of LIDAR data to correct for it. Swift XRT also recorded the highest X-ray flux in its observation on the same day. On the other hand, there are sufficient broadband data to model the SED on MJD 56485.0 (turquoise; middle panel Figure 12), which is less than one day later than the MAGIC and Swift observation of the highest fluxes occurred.

The light curve in Figure 5 shows that Mrk 501 displayed relatively steady emission in each band between MJD 56420 and the elevated state observed by Swift and MAGIC on MJD 56484. In moving from the relatively quiescent SED on MJD 56420 to the elevated state observed on MJD 56485, a hardening of the injection spectrum is required \((q=1.3)\) to match the X-ray spectrum observed by Swift XRT. With the injection index dependent for the hardness of the synchrotron emission at X-ray energies, the frequency at which the synchrotron emission peaks, is related to the spectrum of the injected particle population, and the magnetic field \( (B_0) \). When moving from the state on MJD 56420 to 56485.0, the strength of the magnetic field decreases, moving the peak of the synchrotron emission to lower energies. The decrease of the synchrotron flux resulting from a lower magnetic field is counteracted with an increase of particle luminosity \( L_e \). Finally, to match the relative magnitudes of the synchrotron and inverse-Compton peak fluxes, the electron and photon density of the emission region was increased with a decrease of the emission region size. The decrease of the emission region size to 5.0 \( \times 10^{15} \) cm on MJD 56485.0 provides a higher inverse-Compton flux while maintaining the synchrotron flux.

Following Blumenthal & Gould \( 1970 \), the regime at
Figure 12. Observed broadband SEDs of Mrk 501 on each of the days where NuSTAR observations occurred (red, green, blue and pink data). Additionally we include observations from MJD 56485.0 (turquoise, center panel), which show the SED one day after the most elevated flux state observed during this campaign. The broadband data are represented with a single-zone SSC model (solid line), with the model parameters summarized in Table 6. The Fermi LAT limits shown in the top two panels are taken from analysis of data between MJD 56381 and 56424, while the bottom three panels show Fermi results produced from analysis of data between MJD 56471 and 56499.
Table 6
Single-zone SSC model parameter values (see Section 6 for overview of model and parameters). Model representations are shown along with the broadband data in Figure 12.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>MJD 56395</th>
<th>MJD 56420</th>
<th>MJD 56485.0</th>
<th>MJD 56485.9</th>
<th>MJD 56486.9</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma_{\text{min}} \times 10^4$</td>
<td>2.0</td>
<td>2.1</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>$\gamma_{\text{max}} \times 10^6$</td>
<td>1.0</td>
<td>1.4</td>
<td>1.4</td>
<td>1.7</td>
<td>1.4</td>
</tr>
<tr>
<td>$\gamma_{\text{break}} \times 10^3$</td>
<td>4.1</td>
<td>4.6</td>
<td>2.8</td>
<td>3.3</td>
<td>3.4</td>
</tr>
<tr>
<td>$q$</td>
<td>1.9</td>
<td>1.8</td>
<td>1.3</td>
<td>1.3</td>
<td>1.3</td>
</tr>
<tr>
<td>$\eta$</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>$\delta$</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>$B_0 \text{ [G]}$</td>
<td>0.06</td>
<td>0.05</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>$\Gamma$</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>$R \times 10^{16} \text{ cm}$</td>
<td>7.0</td>
<td>7.0</td>
<td>5.0</td>
<td>7.0</td>
<td>7.0</td>
</tr>
<tr>
<td>$\theta \text{ [degrees]}$</td>
<td>3.8</td>
<td>3.8</td>
<td>3.8</td>
<td>3.8</td>
<td>3.8</td>
</tr>
<tr>
<td>$t_{\text{var}} \text{ [hr]}$</td>
<td>4.3</td>
<td>4.3</td>
<td>3.1</td>
<td>4.3</td>
<td>4.3</td>
</tr>
<tr>
<td>$L_e \times 10^{42} \text{ erg s}^{-1}$</td>
<td>9</td>
<td>12</td>
<td>36</td>
<td>28</td>
<td>26</td>
</tr>
<tr>
<td>$\epsilon = L_B/L_e$</td>
<td>$1.8 \times 10^{-2}$</td>
<td>$6.1 \times 10^{-2}$</td>
<td>$5.3 \times 10^{-4}$</td>
<td>$1.3 \times 10^{-3}$</td>
<td>$1.4 \times 10^{-3}$</td>
</tr>
</tbody>
</table>
which the up-scattering is occurring can be estimated (in the observer frame) according to $4 \nu \gamma_{\text{syn pk}} \gamma / \delta m_e c^2$, where $\gamma$ represents the energy of the electrons up-scattering $\nu_{\text{syn pk}}$ photons. If this quantity is less than 1, the inverse-Compton emission is occurring within the Thomson regime, while if it is greater than 1, the emission is occurring in the Klein-Nishina limit. With $\nu_{\text{syn pk}}$ at approximately 5 keV, $4 \nu \gamma_{\text{syn pk}} \gamma / \delta m_e c^2 \sim 25$, indicating that, according to the model applied within this work, the inverse-Compton scattering of the photons near the synchrotron peak is far into the KN regime. We note that this is not necessarily in conflict with the quadratic relationship between the simultaneous X-ray and VHE flux measurements, but it implies a reasonably steady value of magnetic field which is supported by our SSC models; see Table 6. For a more extensive discussion, see Katarzyński (2005).

The SEDs on the days MJD 56485.9 and 56486.9 are similar to MJD 56485.0. All model representations explored here result in emission scenarios which are heavily dominated (far below equipartition), where the majority of the energy is distributed within the particle population instead of in the magnetic field. Notably, even a single-zone SSC model is difficult to constrain, and the solutions presented here are not applied with the intent of constraining parameter space, but instead to just show that a reasonable representation of the data is possible. There are additional models (e.g. multi-zone or hadronic models) which might alternatively be used to describe the broadband emission from Mrk 501 during these epochs (e.g. Tavecchio et al. 2011; Aleksić et al. 2015b). However, these models have twice as many free parameters as single-zone leptonic models and, in this particular case, there are not strong constraints from MWL flux evolution correlations that point to the necessity of such models.

7. DISCUSSION AND CONCLUSIONS

The inclusion of the hard X-ray telescope NuSTAR in this observational campaign has provided unprecedented insight into the temporal evolution of the 3-30 keV X-rays emitted by Mrk 501. Before this campaign, Mrk 501 had not been observed to display hard X-ray variability on timescales of ~7-hours. The fractional variability of Mrk 501 observed during this campaign was highly significant for the NuSTAR 7-30 keV band ($F_{\text{var}}=0.6$).

Investigation of the DCF allows insight into possible leads or lags between the low (0.3-3 keV) and high (3-7 keV) X-ray and VHE emission. The variability between these two bands shows evidence for a zero day lag. Correlation between the X-ray and VHE bands is further supported by the correlated variability inferred from the Pearson coefficients of 0.958 and 0.954 for simultaneous observations (occurring within one hour), respectively. Correlation is also found between the NuSTAR X-ray flux values and the simultaneous > 200 GeV flux values (with observations occurring within one hour), with Pearson coefficients of 0.974 and 0.979 for the 3-7 keV and 7-30 keV bands, respectively.

Correlation of variability between the X-ray and VHE flux, and more notably direct correlation without any lead or lag time, is a natural signature of SSC emission. Within the single-zone SSC paradigm, the inverse-Compton flux is emerging from the same region as the synchrotron emission, and is fundamentally derived from the same particle and photon populations as the synchrotron emission. In this way, any variability in the synchrotron photon luminosity will immediately be translated into a change in the up-scattered inverse Compton luminosity.

In applying a single-zone equilibrium SSC model to the broadband data of Mrk 501, we find that the data could be reasonably represented in each of the five simultaneous epochs. Notably, the injected particle populations on MJD 56485.0, 56485.9 and 56486.9 are very hard, with an injection index of $q = 1.3$. Such a hard injection index is difficult to produce with standard shock acceleration scenarios alone, but is possible through a magnetic reconnection event (e.g. as explained in Romanova & Lovelace 1992; Siromi & Spitkovsky 2014; Guo et al. 2014). The increase in energy of the particle population (with an additional hardening to the injection index of $q = 1.3$) between the SED derived for MJD 56485.0 as compared to MJD 56420 indicates an introduction of additional energetic particles to the emission region, requiring some source of energy input. The decrease of the magnetic field, similar to what would naturally occur after a magnetic reconnection event, is capable of accelerating particles near the point of reconnection and producing the newly injected $q = 1.3$ particle population. Additionally, the decrease in the emission region size is consistent with a magnetic reconnection event that affects a more localized region as compared to a larger, more steady non-thermal emission region. More information on particle acceleration via magnetic reconnection can be found in Werner et al. (2014) and Guo et al. (2015).

The variability timescale for these model representations, quoted in Table 6, is determined from the light-crossing timescale of the emission region according to $t_{\text{var}} = R / \delta c (1 + z)$. For the emission region sizes and Doppler factor of $\delta = 15$ used within the model, the predicted variability timescales of a couple of hours are compatible with the variability timescale observed during the broadband observations. The radiative cooling timescale is approximately equal to the synchrotron cooling timescale, $t_{\text{cool}} \sim 1.4 \times 10^4 (B_0/0.06 \text{ G})^{-2} \gamma_6^{-1} \text{s}$, where $\gamma_6 = \gamma / (10^6)$. With a minimum light crossing time, corresponding to the minimum variability timescale of $t_{\text{var}} \sim 1.6 \times 10^4 \text{s}$ (in the observer frame), all but the most energetic electrons within the emitting region cool on timescales that are longer than the crossing timescale, showing that the observed variability is likely a reflection of changes in the particle acceleration and/or injection processes directly.

Notably, faster variability timescales have been observed from Mrk 501 in the past (e.g. Albert et al. 2007) and so the model parameters shown here cannot be generalized to all Mrk 501 flux variability episodes. NuSTAR observations show the hard X-ray flux to significantly decrease by more than 10% between its 90-min orbits. Moreover, on MJD 56420 the source hard X-ray flux was observed to change by a factor of greater than 40% in the 7-30 keV band during a 7 hour exposure.

In an attempt to describe a possible emission scenario which might result in the broadband SED variability observed for Mrk 501 in 2013, the parameter changes were made to the single zone equilibrium SSC model monotonically. With a degeneracy between several of the input
parameters, the model applied here cannot be used for
cclusive studies regarding which changes occur within
the emitting region from one state to the next. Instead,
through the study of band-to-band spectral variability,
leads and/or lags and fractional variability, as well as
broadband modeling of various flaring episodes, we find
compelling evidence to support a single zone SSC emission
scenario for Mrk 501 during the broadband observations
in this campaign.

The collection of simultaneous broadband observations
is a necessity for the study of the relativistic emission
mechanisms at work within blazars such as Mrk 501. It
is known that these sources vary continually, with charac-
teristics that significantly change between different flar-
ing episodes, requiring the continuation of deep broad-
band observations such as those presented in this work.

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