

First study of Mrk 501 through the eyes of NuSTAR, VERITAS and the LIDAR-corrected eyesight of MAGIC

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The blazar Mrk 501 is among the brightest X-ray and TeV sources in the sky, and among the few sources whose (radio to Very-High-Energy (VHE; ≥ 100 GeV) gamma-rays) spectral energy distributions can be characterized by current instruments by means of relatively short observations (minutes to hours). In 2013, we organized an extensive multi-instrument campaign involving the participation of *Fermi-LAT*, MAGIC, VERITAS, F-GAMMA, *Swift*, GASP-WEBT, and other collaborations/groups and instruments which provided the most detailed temporal and energy coverage on Mrk 501 to date. This observing campaign included, for the first time, observations with the Nuclear Stereoscopic Telescope Array (*NuSTAR*), which is a satellite mission launched in mid-2012. *NuSTAR* provides unprecedented sensitivity in the hard X-ray range 3-79 keV, which, together with MAGIC and VERITAS observations, is crucial to probe the highest energy electrons in Mrk 501. The multi-instrument campaign covered a few day long flaring activity in July 2013 which could be studied with strictly simultaneous *NuSTAR* and MAGIC observations. A large fraction of the MAGIC data during this flaring activity was affected by hazy atmospheric conditions, due to the presence of a sand layer from the Saharan desert. These data would have been removed in any standard Cherenkov Telescope data analysis. The MAGIC collaboration has developed a technique to correct for adverse atmospheric conditions the very high energy (VHE, $E > 100$ GeV) observations performed by Cherenkov telescopes. The technique makes use of the atmospheric information from the LIDAR facility that is operational at the MAGIC site, and applies an event-by-event correction to recover data affected by adverse weather conditions. This is the first time that LIDAR information has been used to produce a physics result with Cherenkov Telescope data taken during adverse atmospheric conditions, and hence sets a precedent for current and future ground-based gamma-ray instruments. In this contribution we report the observational results, focusing on the LIDAR-corrected MAGIC data and the strictly simultaneous *NuSTAR* and MAGIC/VERITAS data, and discuss the scientific implications.

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1. Introduction

Mrk 501 ($z = 0.034$) is one of the brightest blazars in the X-ray energy band, and is also known to emit very high energy (VHE; $E \geq 100$ GeV) gamma-rays. As well as its continuously high brightness of > 0.3 Crab Nebula Unit (C.U.) in the VHE waveband, this source is known by its fast variability, elevated even up to tens of C.U., and flickering with a time scale as short as 2 minutes [1]. Due to its brightness in a wide waveband range from radio to VHE gamma rays, the spectral energy distributions (SEDs) of this source can be characterized with observations for a relatively short time scale, minutes to hours. Thus, recently, observational campaigns have been coordinated with participation by several instruments, with which the SED of the source can be reproduced by strictly simultaneous observations. Such observations are extremely important for highly variable sources such as Mrk 501, to reduce an ambiguity in the interpretation of SEDs observed in a short flaring state compared with an averaged SED.

For example, a mild activity of Mrk 501 was observed in a campaign in 2009, which included for the first time *Fermi-LAT* data [2], and the campaign revealed that the averaged SED is well described with a simple single-zone synchrotron self-Compton (SSC) model. On the other hand, an analysis of an alternate data set, but still a part of the 2009 campaign [3], showed a variability up to 4.5 C.U. above 300 GeV, as observed by Whipple. This period includes at least two clear flares. It was challenging to model one of the two flares with the standard SSC model using observations between X-ray and VHE instruments, because the correspondence was not clear between a hardening in X-ray spectrum (without catching the synchrotron peak) and varying spectra taken in VHE band. Multi-instrumental campaigns are still quite important to collect various multiwavelength states with simultaneous observations, to have a global picture of the source behavior.

2. Instruments and the observation

In 2013 we organized an extensive multi-instrument campaign including *Fermi-LAT*, MAGIC, VERITAS, *NuSTAR*, F-GAMMA, *Swift*, GASP-WEBT, and other collaborations/groups. This provided the most detailed temporal and energy coverages on Mrk 501 ever, since we have started the organization of the campaigns in 2008. In particular, this campaign included, for the first time, observations with the Nuclear Stereoscopic Telescope Array (*NuSTAR*), which is a space-based hard X-ray telescope launched in 2012. *NuSTAR* provides unprecedented sensitivity in the hard X-ray range of 3-79 keV, which is of particular importance to understand properties of the highest energy electrons injected into the emission region(s) of Mrk 501, together with MAGIC and VERITAS observations. The details of the participating instruments can be found in [4], where the analysis and an expanded interpretation of this campaign are also described.

The campaign covered a few day long flaring activity in July 2013. In the active period, we triggered a Target-of-Opportunity (ToO) observation to get maximum overlap of strictly simultaneous observations between X-rays and VHE instruments, namely, *NuSTAR* and MAGIC observations. The overall light curve obtained is shown in Figure 1. A clear correlation is seen between observed flux values by X-ray satellites (*NuSTAR* and *Swift/XRT*) and by VHE instruments (MAGIC and VERITAS). On the other hand, *Fermi-LAT* observations showed a mild variability,

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for which it is hard to see a clear correlation with other instruments. Possible correlations between the different frequencies were studied. A significant correlation was detected only between the X-ray and the VHE bands. A quadratic function is preferred with respect to a linear function, which naturally indicates that the majority of the inverse-Compton up-scattering of photons is likely to be occurring within the Thomson regime, but does not totally excludes a possibility of having it within the Klein-Nishina regime, as mentioned later.

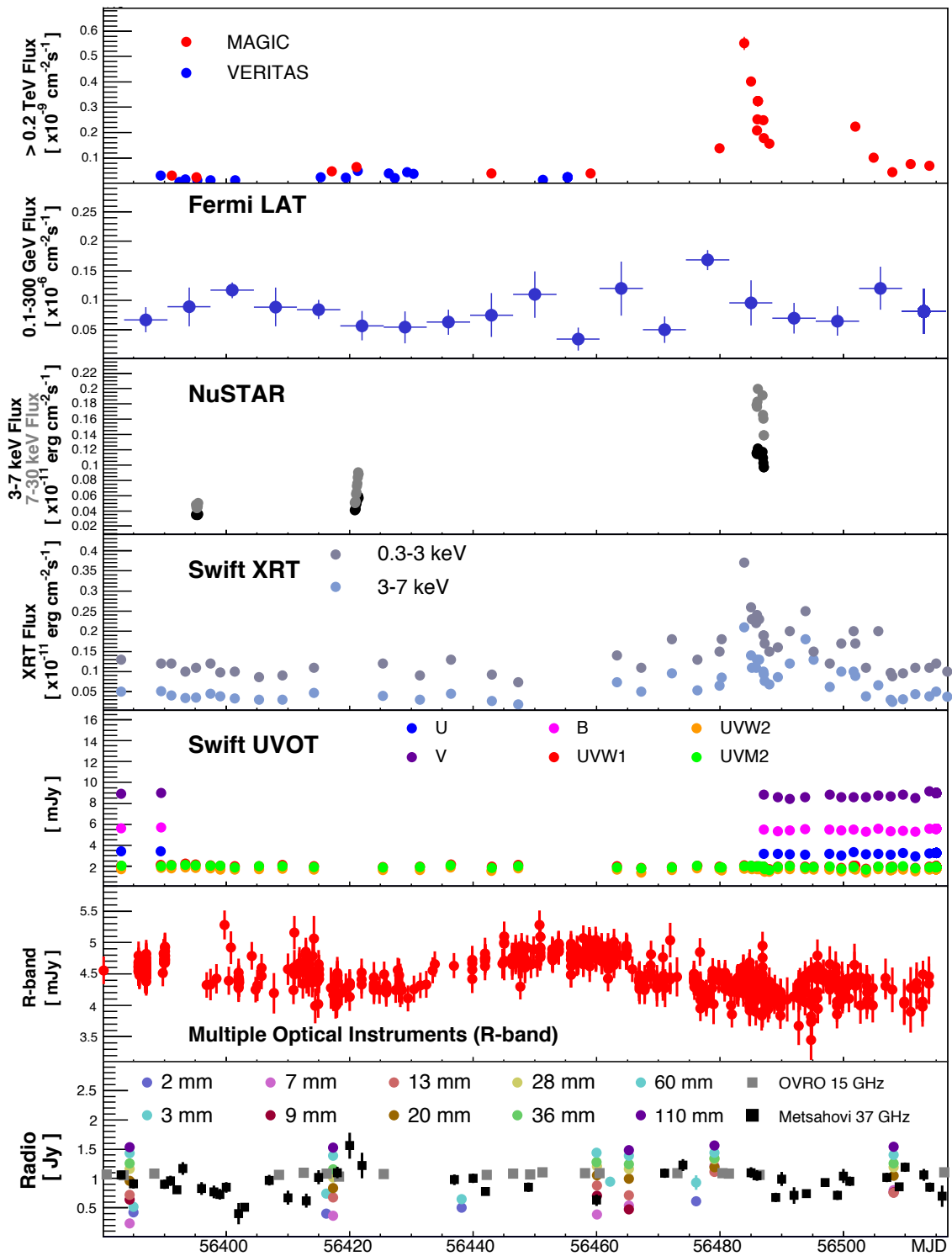
3. LIDAR correction for MAGIC data

In this campaign a large fraction of the MAGIC data were affected by a sand layer from the Saharan desert, in particular during the flaring activity (MJD 56483 and later). Such data would have been removed in any standard Cherenkov Telescope data analysis, due to difficulties in the analysis processes. First, it is challenging to correct event energies of air-showers developed in the dust-ridden atmosphere, especially if the absorption happens at a height close to the shower maximum development. Also, it is difficult to understand the atmospheric transmission profile that is changing in a short time scale of minutes. The former point is not applicable for this case, as the sand layer lies only at relatively low altitude (up to 5 km, typically < 3 km). To overcome the second point, we used information from a LIDAR facility at the MAGIC site, taken during the observation once per 5 minutes. Then, we applied an event-by-event correction in order to reliably use these data. There are two steps in the correction method: one for the estimated energy of each shower event, and the other for the effective area according to the correction in the energy. More details of these correction processes can be found in a contribution in the previous conferences [5, 6]. Recently these analysis processes have been implemented in the standard analysis package in MAGIC, MARS [7]. The method was tested using Crab Nebula observations under non optimal atmospheric conditions.

The MAGIC data points in the overall light curve (Fig. 1) are already corrected by the LIDAR data. Their error bars are applied accordingly, depending on the presence/absence of the LIDAR correction in each analysis. The systematic error of the corrected flux values is estimated to be 15%¹. In the campaign we have collected about 22 hours of the MAGIC data in total, and about 17 hours out of them are affected by the sand layer. Thanks to LIDAR correction, more than 10 hours of the data have been recovered, and we finally obtained 15.1 hours of the usable data in total. The SED of the detected gamma-rays is computed for each day, and is also corrected, accordingly if the day is affected by the sand layer. Figure 2 shows the SEDs for each day, plotted together with corresponding data from all other instruments. The top two panels show SEDs taken in two days (MJD 56395 and 56420) in the former half of the campaign including also *NuSTAR* and VERITAS observations, when the source was in a relatively quiescent state. MAGIC and VERITAS points are colored differently in these two panels.

The highest flux in X-ray observations was recorded in MJD 56484, and in the following day (MJD 56485) we have obtained a good dataset in X-rays (*Swift/XRT*) and VHE (MAGIC, with the LIDAR-correction), as shown in the middle panel. In the following two days we had a more complete campaign including *NuSTAR* observations, which are shown in the bottom two panels,

¹The detailed discussion of the systematic error in the method can be found in [8].



POS (ICRC2015) 755

Figure 1: The broadband light curve of the Mrk 501 observation in 2013 [4] (preliminary).

where MAGIC data are again corrected by the LIDAR data. Note that, *Fermi-LAT* data (shown in grey) were averaged over a period of about a month containing the campaign, due to its limited sensitivity, and so its SEDs in the top two panels and bottom three panels are identical, respectively. Other observations with X-ray and VHE instruments were strictly simultaneous, which enables us to study the temporal evolution of the SEDs without any large ambiguity.

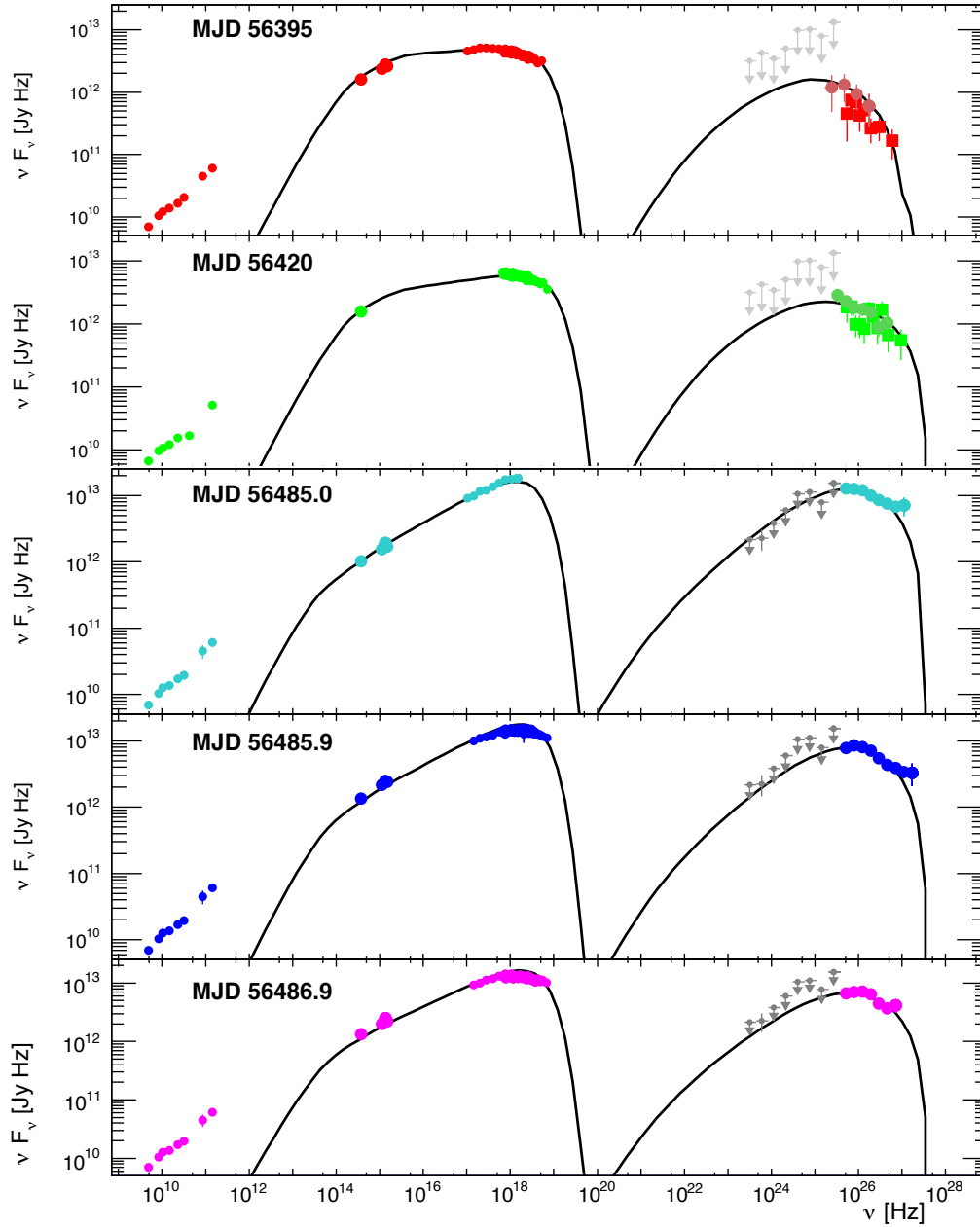


Figure 2: The broadband SED of the Mrk 501 observation in 2013 [4] (preliminary).

Parameter	MJD 56395	MJD 56420	MJD 56485.0	MJD 56485.9	MJD 56486.9
$\gamma_{min} [\times 10^4]$	1.5	2.1	2.0	2.0	2.0
$\gamma_{max} [\times 10^6]$	1.0	1.4	1.4	1.7	1.4
q	1.9	1.8	1.3	1.3	1.3
η	100	100	100	100	100
B [G]	0.06	0.05	0.03	0.03	0.03
Γ	15	15	15	15	15
R [$\times 10^{15}$ cm]	7.0	7.0	5.0	7.0	7.0
θ [degrees]	3.8	3.8	3.8	3.8	3.8
L_e [erg/cm ² /s]	9×10^{42}	12×10^{42}	36×10^{42}	28×10^{42}	26×10^{42}
$\epsilon = L_B/L_e$	1.8×10^{-2}	6.1×10^{-2}	5.3×10^{-4}	1.3×10^{-3}	1.4×10^{-3}

Table 1: Single-zone SSC model parameter values.

4. Results and conclusions

The obtained SEDs are modelled with a simple single-zone SSC model, which is a standard in this source. In particular, it is modeled with an equilibrium version of the single-zone SSC model [9]. The model curves are shown by black lines in Fig. 2, and resultant parameters are seen in Tab. 1. Note that, radio data points are considered as upper limits in the following SED modeling, as it is well known that the source has an extended radio emission outside the region of the jet emission, but affecting the overall flux.

The Doppler factor of the emission region can vary much from state to state. Though there are methods to overcome it, in this work we have simply fixed it to 15, chosen as in the previous studies for Mrk 501 (e.g., [2]). Also, another parameter, η , that determines the escape time scale of the injected particles (by $t_{esc} = \eta R/c$) was fixed to 100, motivated by a success in previous studies for TeV blazars (e.g., [10]). As a result, the temporal evolution of the fitting parameters showed a hardening in the injected particle from the relatively quiescent state on MJD 56420 ($q = 1.8$) to an elevated state on MJD 56485 ($q = 1.3$). Accordingly, the magnetic field (B) of the emission region decreased from 0.05 to 0.03 G, and the equipartition parameter (a ratio of the Poynting flux carried by the magnetic field to the electron kinetic energy, related to the equilibrium particle distribution but not the injected) decreased down to 0.001, which is far from the equipartition. All the parameter behaviours are consistent with a picture that the energy in the magnetic field transferred to the accelerated electrons, to be dominant. One note should be added that the hardening in the injected electrons is difficult to be reconstructed in the standard shock acceleration mechanism, suggesting a possible application of other models such as a magnetic reconnection event (e.g., [11]). A small decrease of the emission region size (R , from 7.0 to 5.0, in the unit of 10^{15} cm) seen in the model fitting is also consistent with this picture. The above modeling indicates that the inverse-Compton scattering of the photons near the synchrotron peak is far into the Klein-Nishina regime. This is not necessarily in opposition to the indication by the quadratic correlation found between X-ray and VHE instruments, as the quadratic correlation can occur even in the Klein-Nishina regime. Such interpretations of the model fitting were discussed in the conference, and are discussed also in [4].

This is the first time that LIDAR information is used to produce a physics result with Cherenkov telescope data taken during adverse atmospheric conditions. The result shows the data can be well corrected and used without any special treatment other than a reasonable increase to the systematic error. This work sets a precedent for the current and future ground-based gamma-ray instruments, such as Cherenkov Telescope Array.

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