Monitoring of Bright Blazars with MAGIC

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***Abstract*. Blazars, a class of Active Galactic Nuclei (AGN) characterized by a close orientation of their relativistic outflows (jets) towards the line of sight, are a well established extragalactic TeV γ-ray emitters. Since 2006, three nearby and TeV bright blazars, Markarian (Mrk) 421, Mrk 501 and 1ES 1959+650, are regularly observed by the MAGIC telescope with single exposures of 30 to 60 minutes. The sensitivity of MAGIC allows to establish a flux level of 30% of the Crab flux for each such observation. In a case of Mrk 421 strong flux variability in different time scales and a high correlation between X-ray/TeV emissions have been observed. In addition, preliminary results on measured light curves from Mrk 501 and 1ES1959+650 in 2007/8 are shown.**

***Keywords*: Active Galactic Nuclei; BL Lacertae objects; gamma-rays observations; gamma-ray telescopes**

I. INTRODUCTION

Blazars belong to the class of AGN and are characterized by relativistic jets oriented towards the Earth. They have a continuous Spectral Energy Distribution (SED) with no or weak emission lines and two broad humps (one in the UV to soft X-ray and a second in the GeV-TeV range). Moreover, their flux was found to be variable at all observed frequencies, but on different time scales ranging form years to minutes [1] [2].

In recent years numerous multiwavelength campaigns were performed with the aim of explaining the acceleration and emission mechanisms in blazars. In many campaigns the new generation of Imaging Atmospheric Cerenkov Telescopes (IACTs) like HESS [3], MAGIC [4] and VERITAS [5] also took part allowing us to have a deeper look at the highly variable VHE (E $\geq$ 100 GeV) γ-ray emission. Unfortunately the data collected so far is not yet enough to fully constrain the theoretical models and still one of the most important question remains unanswered: are the leptonic or hadronic acceleration processes responsible for the observed blazar behavior?

Leptonic models, like for example, the Synchrotron-Self Compton (SSC) [6] are very successful in describing most of the existing SEDs and offer a reasonable explanation for the fast variability of blazars. Hadronic models, on the other hand, like the Synchrotron Mirror Model (SMM) [7] or Synchrotron Proton Blazar (SPB) [8] apart from a good description of the SED structure can also explain the "orphan" γ-ray flares (see e.g. [9]) and predict emission of high energy neutrinos.

II. AGN MONITORING

As mentioned before the new generation IACTs can give a valuable input for understanding of the acceleration mechanism in blazars. Not only by participation in multiwavelength observations, but also by performing a source state independent, long term monitoring of the most interesting brighter γ-ray emitters. There are many advantages of such observations. They allow to obtain an unbiased distribution of flux states and perform any statistical study which requires high statistics on various flux levels. For example: the determination of flaring state probabilities, essential for the estimation of the statistical significance of possible correlations between flaring states and other observables, such as neutrino events [10]. In view of the results expected from the IceCube neutrino observatory [11] such a study is of particular interest.

Investigation of spectral changes occurring during periods of different source activity may also allow to improve our knowledge about the acceleration and emission processes.

Another important aspect of the AGN monitoring is triggering Target of Opportunity (ToO) observations. These follow-up observations may be performed by the IACT issuing the ToO trigger, include other IACTs – allowing to increase the time coverage of the observations – or telescopes and satellites observing at other wavelengths. In a context of "orphan" TeV flares simultaneous X-ray observations are especially valuable.

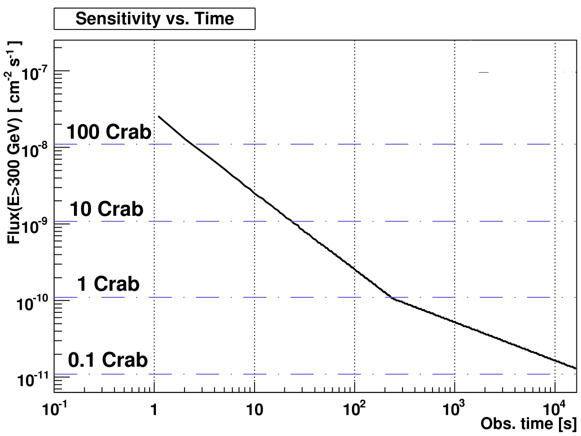

Fig. 1: MAGIC sensitivity corresponding to a 5 σ detection [15] as a function of exposure time.

III. The MAGIC Telescope

MAGIC is currently the largest single-dish IACT for VHE γ-ray astronomy. It is located on the Canary Island of La Palma, at an altitude of 2200 m a.s.l and has been in scientific operation since summer 2004. In January 2007 a major upgrade of the MAGIC Telescope with a Multiplexed Fiber-Optic 2 GSamples/s FADC Data Acquisition system took place [12]. The fast readout minimizes the influence of the background from the light of the night sky and the additional information on the time structure of the shower signal helps to reduce the hadronic background [13]. The trigger threshold of MAGIC is around 60 GeV[1]. A source emitting γ-rays at a flux level of 1.6% of the Crab Nebula can be detected with 5 σ significance within 50 hours of observation time. This sensitivity is sufficient to establish a flux level of about 30% of the Crab flux above 300 GeV for a 30 min observation (Fig.1). A quick on-line analysis system allows to estimate the flux level of the observed source and send ToO triggers on high flux levels during data taking. At present MAGIC is the only IACT which can observe under moderate moon and twilight conditions with only slightly lower sensitivity. The construction of a second telescope (MAGIC-II) is being finalized and it is planned to start stereoscopic observations in autumn 2009 [14].

IV. Monitoring strategy

In order to achieve a dense sampling, up to 40 short observations per source are scheduled, evenly distributed over the observable time by MAGIC. Three sources were chosen for a regular monitoring: Mrk 421, Mrk 501 and 1ES 1959+650. The first two are relatively bright and usually 15-30 min observations are scheduled for them. 1ES 1959+650 being fainter requires longer observation times, at least 30 minutes per single exposure.

[1]The trigger threshold is defined as the peak of the energy distribution of the triggered events.

The major part of the monitoring (∼60%) has been performed under moderate moonlight or twilight, keeping the impact on the overall observation schedule low and allowing to maximize the available duty cycle up to ∼12%.

V. Results

In this section we present the preliminary results of the MAGIC AGN monitoring program for the observation season 2007/2008 together with some previously taken, published MAGIC data on the same objects. The data have been processed with the standard MAGIC analysis tools [4]. A fraction of the data has been removed due to poor observation conditions. All cuts were optimized and verified with Crab Nebula data.

A. Mrk 421

Between February 2007 and June 2008 82 hours of data from Mrk 421 were taken. The observations were mostly performed in wobble mode, which allows to simultaneously collect signal and background events. About 66 hours of good quality data (80%) were used for further analysis. It should be noted that about 70% of these data were taken due to the ongoing flaring activity of the source and are actually not part of the monitoring campaign.

All observations of Mrk 421, performed by MAGIC since 2004 [16] [17], are shown in Fig.2. The source was very active in 2008: many flares were observed and flux rarely decreased below 1 Crab level ($F_{E>300\,GeV}$ $= 1.23 \pm 0.10) \times 10^{-10}$ ph/cm^{-2}s^{-1} [4]). According to a ToO agreement with HESS and VERITAS, MAGIC issued several alerts during this time of high activity. A detailed analysis of the collected data, such as a study on the intra-night variability is discussed in [18].

As mentioned before, possible correlations between different wavelengths, in particular TeV γ-rays and X-rays, are an interesting subject to investigate. We therefore searched for X-ray and optical measurements which are within 6 h before or after the TeV observations. In this work we used the X-ray data taken by the ASM instrument aboard of the RXTE satellite, which are publicly available on the project[2] web page. The averages and errors of ASM data points were calculated on a dwell-by-dwell (90 seconds) data basis. If the number of dwells were fewer than five, we discarded that data point. We finally selected 75 pairs of TeV-X-ray measurements for further analysis.

The 1.03 m telescope at the Tuorla Observatory Finland and the 35 cm KVA telescope at La Palma, Canary Islands provided us with the optical R-band data from their Blazar Monitoring Program[3]. The optical flux was corrected for the flux of the host galaxy and the flux contribution from the companion galaxies [19]. In the end, 56 measurements pairs were found.

[2]http://xte.mit.edu/ASM_lc.html
[3]http://users.utu.fi/kani/1m/

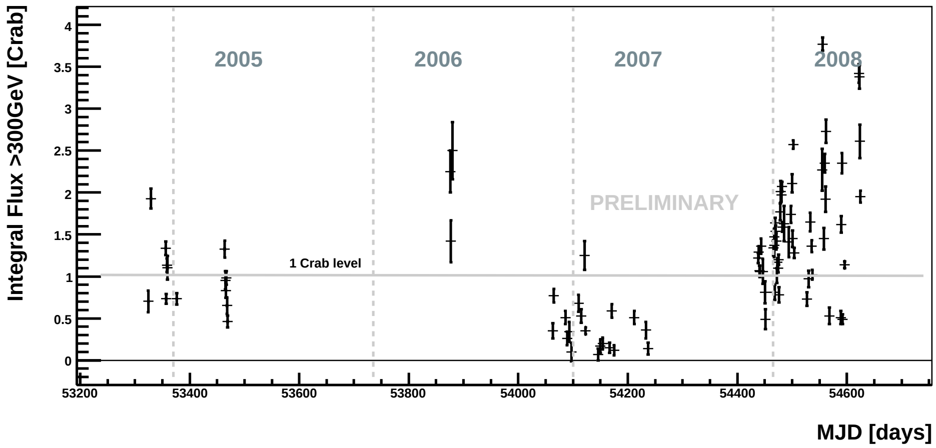

Fig. 2: Mrk 421 light curve showing all data collected by MAGIC [16] [17] so far.

We used the Pearson's method (see section 14.5 in [20]) to calculate the correlation coefficients. For the X-ray/TeV data set (shown in Fig.3 left), the correlation coefficient value is r = 0.77±0.05 and for optical/TeV data (Fig.3 right), the coefficient becomes r = 0.03±0.14.

The significant (8 σ) correlation with X-rays we found might point to a leptonic origin of the emission (see e.g. [21] and references therein) but certain hadronic models also predict such a correlation (see e.g. [8] or [22]). In any case, conclusions on the origin or mechanism of the emission should be made very carefully because the data were not taken strictly simultaneously.

B. Mrk 501

Fig. 4 shows all the data collected from Mrk 501 by the MAGIC telescope since 2005, when the source was found in a flaring state and doubling times as short as few minutes were observed [2]. The new results presented here are based on the data collected between February 2007 and August 2008. As in the case of the Mrk 421, the observations were performed in wobble mode, mostly during moderate moonlight or twilight in order to maximize the time coverage of this source (56% of the total observation time). After quality selection 16 hours of data remained and were analyzed. A part of the light curve presented in Fig. 4 was taken during a multiwavelength campaign (MJD 54550-54602) described in more detail in [23]. Similar to the year 2006 [17] in the 2007/2008 observational period Mrk 501 was in a relatively low state (below 1 Crab). Thanks to good weather conditions at the site a dense sampling was obtained. A statistical analysis, e.g. estimation of the source state probability, is in progress.

C. 1ES 1959+650

MAGIC monitored 1ES 1959+650 from April 2007 till October 2008 for 27 hours under large zenith angle (35°-50°) conditions. The source was observed in wobble mode. After quality selection mainly based on bad atmospheric conditions and unstable, low event rates,

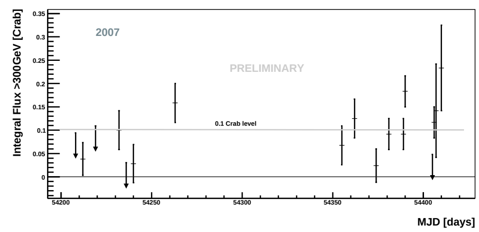

Fig. 5: 1ES 1959+650 light curve showing MAGIC data from the year 2007. The arrows denote upper limits at 90% C.L.

12.7 hours of data taken in 2007 and 3.6 hours of data taken in 2008 were analyzed.

In 2007 a clear γ-ray signal of 9.0 σ is seen. However, the mean 1ES1959+650 γ-ray flux above 300 GeV during this observations period with MAGIC was only $(0.92 \pm 0.12) \times 10^{-11}$ ph/cm^{-2}s^{-1}, i.e. ~10% Crab. The overall light curve for 1ES1959+650 in 2007 is shown in Fig. 5, all measurements with significances below 1 σ were converted to flux upper limits. The light curve indicates no major changes of the flux level and no significant flares. The overall significance of the data sample from 2008 is 2.6 σ, which allows us to set an upper limit on the flux above 300 GeV of 1.54×10^{-11} ph/cm^{-2}s^{-1} at 90% C.L. In comparison to previous observations [24] [25] it can be concluded that MAGIC observed 1ES1959+650 in 2007/2008 during its usual quiescent state.

VI. CONCLUSIONS

During the observational season 2007/2008 three blazars were regularly monitored by MAGIC: Mrk 421, Mrk 501 and 1ES 1959+650. Here we presented preliminary results of the measured flux levels for all three sources. Mrk 501 and 1ES 1959+650 were found in a low state, but the dense sampling of Mrk 501 provides valuable material for further statistical studies. Mrk 421 has shown an interesting flaring activity in 2008. We also investigated possible correlations of the TeV and

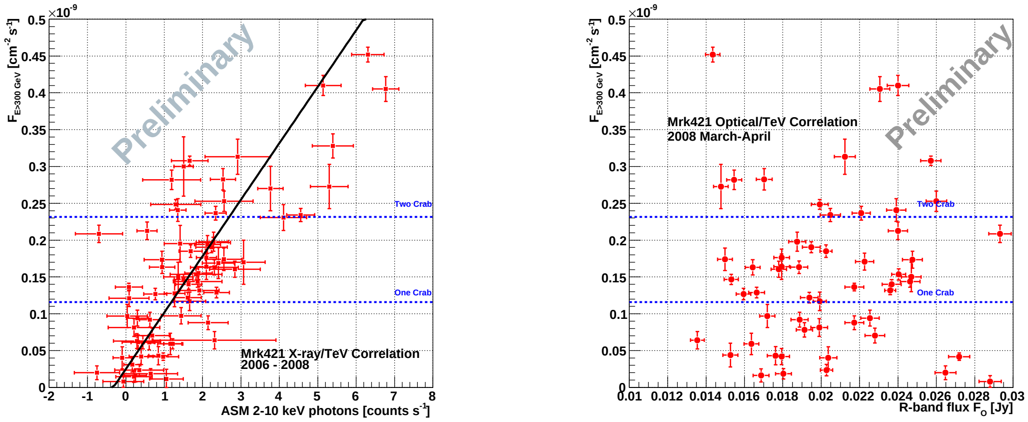

Fig. 3: Left: VHE γ-ray (MAGIC) - X-ray (ASM) correlation plot for Mrk 421. Right: VHE γ-ray (MAGIC) - R-band (KVA) correlation plot for Mrk 421.

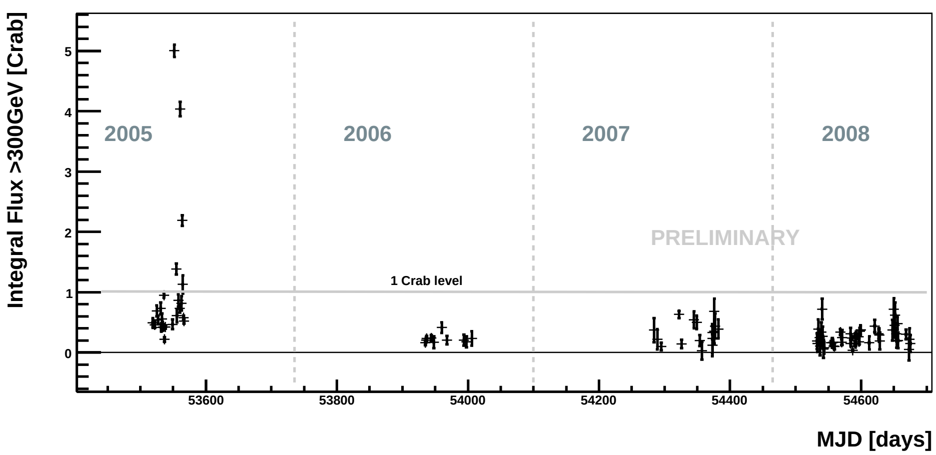

Fig. 4: Mrk 501 light curve showing all data collected by MAGIC [17] [2] so far.

X-ray/optical flux levels for Mrk 421. We found a significant correlation between TeV and X-rays but no correlation with the optical R-band. Parts of the data collected from Mrk 421 and Mrk 501 are discussed in more detail in dedicated contributions [18] [23].

VII. The Acknowledgments

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