The connection between optical and VHE γ-ray high states in blazar jets

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***Abstract*. MAGIC has been performing optically triggered Target of Opportunity observations of flaring blazars since the beginning of its scientific operations. The alerts of flaring blazars originate from Tuorla blazar monitoring program, which started the optical monitoring of the candidate TeV blazars in 2002 and has now collected up to six years of data on 30 blazars. These Target of Opportunity observations have resulted in the discovery of three new VHE γ-ray emitting blazars (Mrk 180, 1ES 1011+496 and S5 0716+714) and in addition the discoveries of BL Lac and 3C 279 were made during a high optical state. In this talk we present a detailed analysis of the optical light curves which are then compared to MAGIC observations of the same sources. We aim to answer the question "Is there a connection between optical and VHE gamma-ray high states in blazars or have we just been lucky?"**

***Keywords*: blazars, observations, multiwavelength**

I. Introduction

Blazars are the most extreme type of Active Galactic Nuclei (AGN). In these objects the dominant radiation component originates in a relativistic jet pointing nearly towards the observer. Blazars show a variable flux in all wave bands from radio to very high energy (VHE, here defined as E> 100 GeV) γ-rays. The relationship between the variability at different wave bands appears to be rather complicated. It is generally assumed that the energy spectrum is dominated at lower energies (radio-UV and even up to X-rays in some sources) by synchrotron radiation from relativistic electrons spiraling in the magnetic field of the jet, and at higher energies (X-ray to VHE γ-rays) by inverse Compton scattering. Seed photons for inverse Compton scattering can be local or co-spatial synchrotron photons (synchrotron self-Compton, SSC), or external photons (EC) originating from the accretion disk [1], emission-line clouds [2], or the molecular torus [3]. In the simplest case both SSC and EC mechanisms predict a connection between optical and γ-ray flares. Time-lags between optical and γ-ray flares may be present due to several mechanisms (see e.g. [4], [5] for detailed discussion). The time-lags and their relative order (an optical flare leading a flare in γ-rays or vice versa) are impossible to predict. The connection between optical and γ-ray flares should also depend on the synchrotron peak frequency of the source. If the peak position is at a much higher frequency (in the X-ray domain) the variability in the optical band is in some cases very small and the synchrotron flares are best visible in the X-ray band. This seems to be the case for the best studied TeV blazars Mrk 421 [6] and Mrk 501 [7]. In principle, hadronic models can also explain correlated variability and cannot be excluded as the emission mechanism of γ-rays.

The MAGIC collaboration is performing Target of Opportunity observations of sources in a high flux state in the optical, and/or X-ray band. Alerts of optical high states are sent by the Tuorla Blazar Monitoring Program ([8],). These triggered MAGIC observations and resulted in discovery of VHE γ-rays from Mrk 180 [9], 1ES 1011+496 [10], and S5 0716+714 [11]. In this paper, we present analysis of the optical light curves and compare them to the simultaneous MAGIC observations. We discus the implications of the results to the optical- VHE γ-ray connection.

II. Tuorla Blazar Monitoring Program and the Analysis of the Optical Light Curves

The observations are performed with the KVA 35 cm telescope, which is remotely operated from Tuorla Observatory and the Tuorla 1 meter telescope. The observations are made in the R-band and the magnitudes are measured using differential photometry with calibration stars in the same CCD frame as the object. The light curves are updated to the project web page http://users.utu.fi/kani/1m/ on a daily basis.

The long term monitoring program consists of 24 objects, which were chosen from list of candidate TeV blazars [12] with declination $> 20^o$ for them to be observable from Tuorla. The monitoring started in 2002 and the goal of the monitoring is to study the optical variability of these sources and to determine the baseline flux. We have also made study of the host galaxy contribution to the objects overall brightness [13]. This way we can get direct measurement of the AGN core brightness by subtracting the host galaxy distribution. The collected information has been used to define the trigger criteria for Target of Opportunity program. As

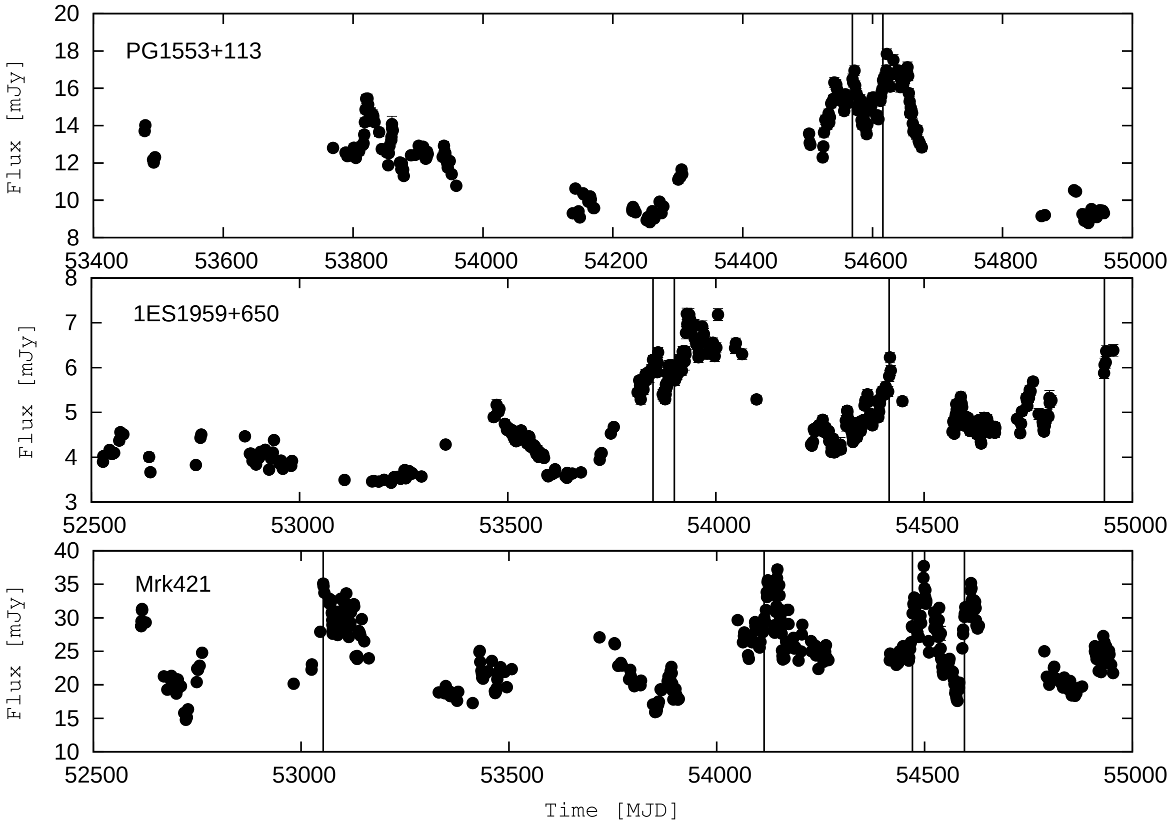

Fig. 1. Optical light curves of Mrk 421 (bottom), 1ES 1959+650 and PG 1553+113 from the Tuorla blazar monitoring program. The vertical lines in the light curves indicate the flares that fulfilled the triggering criteria of the MAGIC ToO proposal.

the program has been proven to be successful (discovery of three new VHE γ-ray emitters following the optical alerts), we have added $\sim$ 20 more blazars to the monitoring program. For analysis we chose 29 best sampled optical light curves (23 from the original sample and 6 additional ones: S5 0716+714, W Com, 3C 279, PG 1553+113, H 1722+119, PKS 2155-304).

To define the flaring states from the optical light curves, we have used the criteria of 50% of increase of the core flux compared to quiescent level. The quiescent flux level has been determined by visual inspection of light curves, but has generally followed the rule that source spends $\sim 20\%$ of the time below and within this level. A more detailed study of the quiescent states and definition of flaring states is in preparation, but following this simple criterium our light curves reveal 53 optical flares.

III. Optical to VHE γ-ray comparison

The MAGIC telescope [14] is performing Target of Opportunity observations of blazars when the blazars are in a high optical state. Therefore, for quite many flares simultaneous or quasi-simultaneous optical data exists. Of the total of 53 optical flares, 43 occured after the beginning of Cycle 1 in MAGIC (June 2005). For 30 flares there is some simultaneous MAGIC data, but only for 18 flares there is more than 3 hours of good quality data. This is mostly constrained by the weather and moon conditions as well as conflicts in the MAGIC schedule. In 11 cases the source was detected by MAGIC. These 11 flares were detected in 9 sources: Mrk 421, 1ES 1959+650, PG 1553+113, 3C 66A, 3C 279, BL Lac, Mrk 180, 1ES 1011+496, S5 0716+714 (see Fig. 2). In 7 cases the MAGIC observations resulted with upper limit.

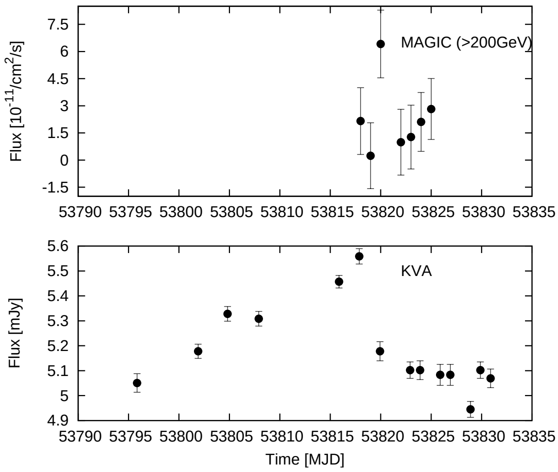

Fig. 2. Light curve of Mrk 180 from MJD 53790-53835 (2006, February 24 - April 10). *Lower panel*: the optical light curve from the KVA telescope. *Upper panel*: the MAGIC light curve.

The only source for which a real correlation study is possible is Mrk 421, because it is the only one for which we have good time coverage with MAGIC. Preliminary results on this study will be presented [15]. For 1ES 1959+650 the optical flare occured in spring 2006 (MJD ~ 53800, see Fig. 2), when the source was in a very low state at VHE γ-ray regime [16]. PG 1553+113 was in high state in optical in spring 2008, when it was also detected to have a higher VHE γ-ray flux than in 2007 (in lower optical state) [17]. We exclude 3C 66A from our comparison, it is discussed in [18], but it should be mentioned that the discovery of VHE γ-rays from 3C 66A by VERITAS was done during a optical flare [19].

For other sources we need to compare single discovery observations and the follow-up or previous observations in lower optical state. There is now a second observation by MAGIC for all the discovered sources , which has been performed in a lower optical state. For Mrk 180 the analysis of the follow-up observation from October-December 2008 is still ongoing. For 1ES 1011+496 the observation from 2006 [20] showed only weak evidence for a VHE γ-ray signal at 3.5σ. The VHE γ-ray flux was $> 40\%$ higher in March-May 2007 than in March-April 2006. For S5 0716+714 the November 2007 flux (low optical state) is about 8 times lower than April 2008 flux (high optical state) [11]. BL Lac was only detected in 2005 observation period but not in 2006, when it was in signicantly lower optical state. The case for 3C 279 is more complicated. In February 2006 when MAGIC first discovered it [21], it was in a rather high optical state, but not fulfilling the triggering criteria. In January 2007, when the observations were triggered by the optical high state (and the optical flux was three times higher that in February 2006), a preliminary analysis shows a detection the source by MAGIC [22]. As the analysis of the 2007 data is still ongoing, the comparison of flux levels between February 2006 and January 2007 is not yet possible.

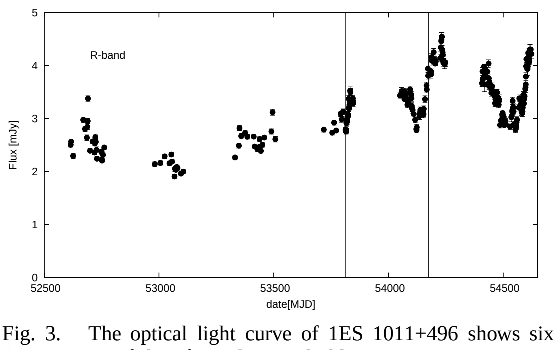

Fig. 3. The optical light curve of 1ES 1011+496 shows six years (2003-2008) of data from the Tuorla blazar monitoring program. The vertical lines indicate the starting points of the MAGIC observations in 2006 [20] and 2007 [10]

For non-detected sources the results from the MAGIC observations have not been published yet, with the exception of OJ 287 during the December 2007 outburst [23], [24]. However, for non-detected sources even the flaring state VHE γ-ray flux might be below the MAGIC

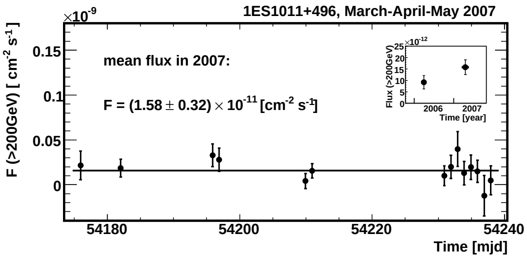

Fig. 4. The VHE γ-ray light curve of 1ES 1011+496 from March 17th (MJD 54176) to May 18th (54238) 2007. The inset shows the yearly averages from 2006 and 2007.

sensitivity. Therefore, the only source which shows clear evidence that the VHE γ-ray flux does NOT follow the optical flux states is 1ES 1959+650. Interestingly, for this source also lack of correlation between X-rays and VHE γ-rays has been observed [27].

IV. Discussion and Outlook

The optically triggered Target of Opportunity observations have resulted in the discovery of three new VHE γ-ray emitting blazars. Mrk 180 and 1ES 1011+496 are classified to be HBLs, while S5 0716+714 is classified as IBL or even LBL. However, the BL Lac population is continuous rather than bimodal or trimodal (see, e.g. [25], [26]), and in all of the three discovered sources the synchrotron peak frequency is not too far from the optical band (see e.g. publicly available data at *asdc.asi.it/blazars* and Fig. 6. in [10]). If the synchrotron emission and the IC emission arise from the same emission region, the connection between optical and VHE γ-rays would be expected. On the other hand, it can be that in some sources there is no connection between optical and VHE γ-ray flaring (e.g. different emission regions, different mechanisms etc.).

There seems to be at least 6 sources which suggest connection between optical and VHE γ-ray high states and only one source where clearly no connection is seen. Unfortunately the current data from VHE γ-ray range does not allow more definite conclusions.

Acknowledgments

MAGIC enjoys the excellent working conditions at ORM and is supported by the German BMBF and MPG, the Italian INFN, the Spanish MCI-NN, ETH research grant TH 34/04 3, the Polish MniSzW Grant N N203 390834, and by the YIP of the Helmholtz Gemeinschaft. E.J.L wishes to acknowledge the support by the Academy of Finland grant 127740. D.M's research was supported by a Marie Curie Intra European Fellowship within the 7th European Community Framework Programme.

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