Studying flux variability of the BL Lac object 1ES0806+524 with MAGIC in a multi-wavelength context

K. BERGER[1], C. SCHULTZ[2], E. LINDFORS[3,4] R. RHEINTHAL[4,5], A. STAMERRA[6], F. TAVECCHIO[7] FOR THE MAGIC COLLABORATION, S. BUSON[1], F. D'AMMANDO[8] FOR THE *Fermi* COLLABORATION AND T. HOVATTA[9] FOR THE OVRO COLLABORATION

[1] *Delaware University, 19711 Newark, DE, USA*
[2] *Università degli Studi di Padova & INFN Padova, I-35131 Padova, Italy*
[3] *Finnish Centre for Astronomy with ESO (FINCA)*
[4] *University of Turku, Finland*
[5] *Tuorla Observatory*
[6] *Università di Siena & INFN Pisa, I-3100 Siena, Italy*
[7] *INAF National Institute for Astrophysics, I-00136 Rome, Italy*
[8] *University of Perugia & INFN, I-06123 Perugia, Italy*
[9] *Cahill Center for Astronomy & Astrophysics, California Institute of Technology, CA 91125, USA*

berger.karsten@gmail.com

Abstract: We present results of multi-wavelength (MWL) observations of the high-frequency-peaked BL Lacertae (HBL) object 1ES 0806+524 (z=0.138, [1]). Triggered by a high optical state, very high energy (VHE; E > 100 GeV) observations were carried out with the MAGIC stereoscopic system from January to March 2011. During the observations a relatively short VHE γ-ray flare was detected that lasted no longer than one night. To complement the VHE observations, simultaneous MWL data were collected in high energy γ-rays using the *Fermi* Large Area Telescope (HE, 300 MeV - 100 GeV), in the X-ray and UV band with the *Swift* satellite, in the optical R-band through observations with the KVA telescope and in the radio band using the OVRO telescope. This constitutes the first time that such a broad band coverage has been obtained for this source. We study the source properties through the characterization of the spectral energy distribution (SED) and its evolution through two different VHE flux states. The SED can be modeled with a simple one-zone SSC model, resulting in parameters that are comparable to those obtained for other HBLs.

Keywords: Gamma rays: galaxies – BL Lacertae objects: individual: 1ES 0806+524

1 Introduction

Active galactic nuclei (AGN) are among the most variable objects in the known universe. Their broad band energy spectrum spanning from radio to very high energy (VHE, E > 100 GeV) γ-rays can be characterized by two distinct peaks: one in the optical to UV range, commonly interpreted as synchrotron radiation, and a second one in the γ-ray band that is supposed to originate from inverse Compton scattering of synchrotron photons. The discovery of several AGN in VHE γ-rays during high optical states [2] leads to the suggestion that optical and VHE γ-ray high states are connected. In some cases, long–term studies of the broad band emission seem to confirm such a conclusion [3], whereas in other sources this seems to be only partially the case [4, 5].

1ES 0806+524, classified as high peaked BL Lacertae object (based on the peak of the synchrotron emission and a featureless optical spectrum [6]) was suggested as a VHE candidate by [7]. Several VHE observations have been carried out [8, 9, 10], but initially no emission was found. Finally, VERITAS observations from November 2006 to April 2008 succeeded to detect the source in a non-variable, low emission state (integral flux E>300 GeV equal to ~1.8% of the Crab Nebula flux [11]).

This proceeding reports MAGIC observations during a high optical state in early 2011. We analyze flux and spectral variability in VHE γ-rays and model the spectral energy distribution including complementary data from contemporaneous observations in HE γ-rays carried out by the *Fermi* Large Area Telescope (LAT), in X-rays performed by the *Swift* satellite and in the optical R-band by the KVA. Radio data coverage is provided by the OVRO telescope at 15 GHz.

2 MAGIC observations

MAGIC is a stereoscopic system of two 17 m Imaging Atmospheric Cherenkov Telescopes (IACTs) located at the Roque de Los Muchachos, La Palma, Canary Islands (28.8° N, 17.8° W, 2225 m a.s.l.). Due to its low energy threshold (~60 GeV) and high sensitivity[1], it is well suited for VHE γ-ray observations of blazars.

Observations carried out between January and March 2011 on 13 nights for a total of ~24 h resulted in a flare detection on February 24th (7.6 σ above 250 GeV [13]) and a strong overall detection of ~9.9 σ above 250 GeV within 16.1 h of effective observation time. The observations were triggered by a high optical state of the source reported by the KVA telescope in the framework of the Tuorla blazar monitoring program.

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1. E>290 GeV; flux <0.8% of the Crab Nebula in 50 h [12].

3 The MWL context

Figure 1 shows the long-term MWL light curves in VHE γ-rays (MAGIC), HE γ-rays (*Fermi*-LAT), X-rays (*Swift*), in the R-band (KVA, Tuorla) and radio regime (OVRO telescope).

The source showed hints of variability in HE γ-rays evidenced by a low probability of 6% for constant emission during the period of interest. A smooth flux increase from the beginning of March until the beginning of April 2011 reaching a maximum of $(7.5 \pm 1.5) \cdot 10^{-8}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ (E > 300 MeV) was observed with a delay compared to the other wavelengths followed by a steady decrease. Given the long integration time of seven days, no clear conclusion regarding simultaneous source variability can be drawn.

In X-rays (2–10 keV) the time–averaged flux is $(8.7 \pm 1.0) \cdot 10^{-12}\,\mathrm{erg\,cm}^{-2}\,\mathrm{s}^{-1}$ showing an enhancement on March 2nd to $(13.0 \pm 0.5) \cdot 10^{-12}\,\mathrm{erg\,cm}^{2}\,\mathrm{s}^{-1}$, with indications of spectral hardening [14]. Compared to previous observations performed on February 1st, 2011, the measured flux is 2–3 times higher and is comparable to the flux level measured in March 2008 during the first detection of the source in VHE γ-rays. Hence, the *Swift*/XRT observations confirm the high activity state of the source exhibiting a clear variability in X-rays with a probability of a constant flux of $6.9 \cdot 10^{-21}$.

Swift/UVOT observations were carried out with different filters in the ultraviolet bands. The brightness of (14.4 ± 0.03) mag measured on March 2nd in the UV-W2 and UV-M2 bands is almost unchanged with respect to February 1st where a brightness of (14.5 ± 0.03) mag was measured. However, 1ES 0806+524 appears about 1 mag brighter compared to the UV flux observed in March 2008. During the observations the UV band photometry is compatible with a constant flux.

In the R-band, the core flux was seen to have greatly increased over the long–term base level (2.8 mJy) starting from November 2010. Over the following months the flux density continued to increase until reaching a maximum of (4.75 ± 0.09) mJy (host galaxy subtracted), an almost threefold increase over the quiescent state of 1.72 mJy [2] on the night of February 24th, 2011, during the outburst in VHE γ-rays, after which the flux level began to decrease steadily.

The long–term radio light curve provides a probability of $\sim 6.2 \cdot 10^{-5}$ for a non–variable source with an average flux level of 0.14 Jy. A correlation between the high γ-ray state and a possible flux increase in the radio band to 0.15 Jy is observable. However, due to the large statistical error, the flux is compatible with the flux level of the night before and after the VHE γ-ray flare. Compared to observations from November 2010, the radio data show a marginal flux increase from mid–January to May 2011, exceeding the mean flux level of the overall observation period.

4 Theoretical modeling and interpretation

The spectral energy distributions of the source describing the high and low state during the MAGIC observations, together with simultaneous data from *Fermi*, *Swift*, the KVA and OVRO telescopes are presented in Figure 2 and Figure 3. EBL corrections have been applied to the VHE γ-ray data using [17]. Data from *Swift*/UVOT and optical data in the R-band provided by the KVA telescope have been corrected for galactic extinction and the host galaxy contribution respectively [15, 16].

| SSC parameter		Source state high	low
γ_{min}	$[10^3]$	1.0	1.0
γ_{b}	$[10^4]$	2.0	2.0
γ_{max}	$[10^5]$	7.0	7.0
n_1		2.0	2.0
n_2		3.85	3.90
B	[G]	0.05	0.05
K	$[10^3\,\mathrm{cm}^{-3}]$	19	4.0
R	$[10^{16}\,\mathrm{cm}]$	1.17	1.90
δ		28	28
P_{e}	$[10^{43}\,\mathrm{erg/s}]$	44.8	22.0
P_B	$[10^{43}\,\mathrm{erg/s}]$	0.10	0.26
P_{p}	$[10^{43}\,\mathrm{erg/s}]$	7.7	3.3

Table 1: Input and output parameters of the SSC model (described in section 4) are reported for the high and low state SED presented in Figures 2 and 3. The derived power carried by electrons, magnetic field and protons is also shown.

Simultaneous and quasi-simultaneous data have been combined in such a way, that they cover the high and low state as observed in VHE γ-rays. Unfortunately, the *Fermi*–LAT cannot detect 1ES 0806+524 on time scales shorter than one week. To provide simultaneous coverage in this energy band for the high state of the source, an upper limit was calculated for February 24th which was included in the SED modeling. In addition, an averaged SED from eight months of observations taken from November 2010 to June 2011 has been derived and is shown for comparison in Figure 2. For the low state, an averaged spectrum from January to March 2nd was produced in this energy band excluding the night of the γ-ray flare from the data sample.

Archival data in the radio band (from NED), and the R–band (from [11]) are also shown in gray. The *Swift* data were divided into high state (February 27th and March 2nd) and low state observations (February 1st to March 1st). Since no variability in the radio band was detected during the MAGIC observations, all available data were included for both source states.

MAGIC observations indicate flux variability of a factor of three in VHE γ-rays, whereas the comparison of the low state data from *Fermi* with the eight–months averaged spectrum does not indicate any significant variation in the HE regime. As observations in the U–band have been carried out in "filter of the day" mode, no explicit comparison between the two activity states of the source can be made. A continuous flux increase in the R–band is present, starting well before 1ES 0806+524 showed flaring activity in the VHE regime and in X-rays, which exhibits a plateau with only marginal flux variations towards the end of February. No significant difference is seen in the synchrotron component, while the flux of the inverse Compton peak increases by a factor of 2∼3. The large uncertainty in the HE γ-ray band limits the determination of the inverse Compton peak.

A one–zone synchrotron–self–Compton (SSC) model is applied to reproduce the SED of both source states (for a detailed description see [18]), where a spherical emission region of radius R is assumed, filled with a tangled magnetic field of intensity B. A population of relativistic electrons is approximated by a smoothed broken power law
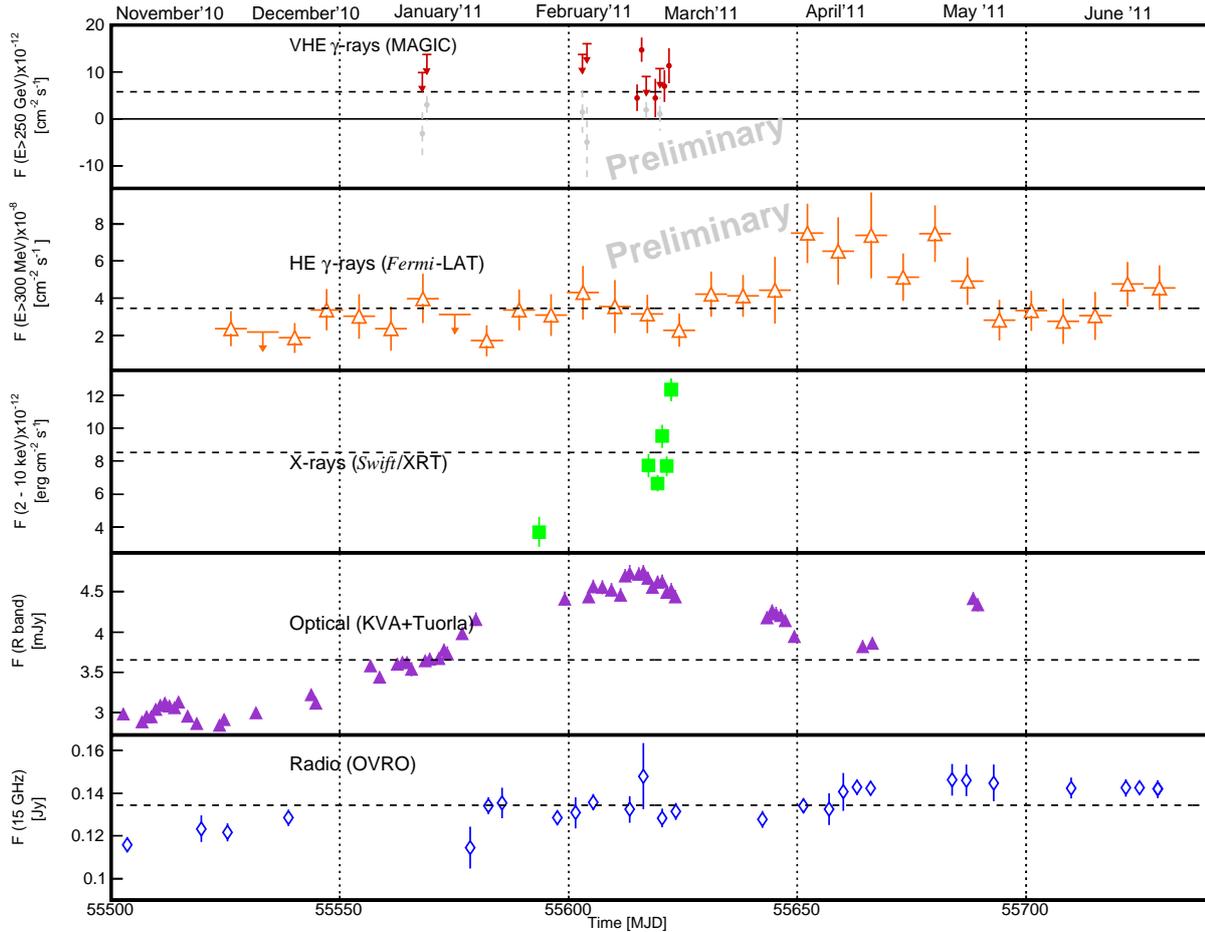
Fig. 1: From top to bottom: MWL light curve of 1ES 0806+524 from December 2010 to June 2011 covering VHE γ-rays (red and gray circles) by MAGIC, HE γ-rays (orange triangles) by *Fermi*–LAT, X-rays (green squares) by *Swift*/XRT, R–band (violet triangles) and radio (blue diamonds) by the KVA and OVRO telescopes. 95% confidence upper limits are indicated as downward arrows in VHE γ-rays where the flux is compatible with zero as well as in the HE band for each time bin where the test statistic (TS) value for the source was TS<9. The individual light curves are daily binned except for the light curve in the HE band, where a weekly binning has been applied. The mean flux levels of the respective observation periods are indicated (dashed lines).

that is parametrized by the minimum, break and maximum Lorentz factors γ_{min}, γ_b and γ_{max} as well as the slopes n_1 and n_2 before and after the break, respectively. Relativistic effects are taken into account via the Doppler factor δ.

We report the physical parameters derived for both source states in Table 1. The values are similar to those typically inferred for other HBL objects (see e.g. [19]). Most of the physical parameters referring to the electron spectrum of the high and low state are compatible, except the electron density K, which shows an increase by a factor of ~ 5 during the high state. Furthermore, the emission region R during the high state is approximately half the radius of the emission region of the low state.

In Table 1 we also report the power carried by the jet through electrons (P_e), magnetic field (P_B) and protons (P_p), derived assuming the presence of one cold proton per emitting electron. Magnetic field and protons appear subdominant with electrons carrying most of the jet power, whose total value, $P_{jet} = P_e + P_B + P_p \sim 10^{44}$ erg s^{-1} is also typical (e.g. [20]). While the jet power carried by the electrons and protons doubles during the flare, the magnetic field power is reduced. The minimal variability time scale of the

model (~ 0.2 days based on a causality argument) is compatible with $\sim$one day flux doubling time inferred from the VHE light curve.

5   Summary & Discussion

We reported MAGIC observations of the HBL 1ES 0806+524 in early 2011, triggered by an optical high state. MAGIC caught a short (one day) VHE γ–ray flare with a VHE flux increase of a factor of three. Excluding the flare, the VHE γ-ray flux from the source was in good agreement with VERITAS observations in 2008 [11].

The MWL data show variability across the electromagnetic spectrum. While the optical and VHE γ-ray flares have been accompanied by an outburst in X-rays, an increase of the HE flux has been observed later and on longer time scales. Although the VHE observations were optically triggered, no apparent evidence of a correlation was found between these wave bands.
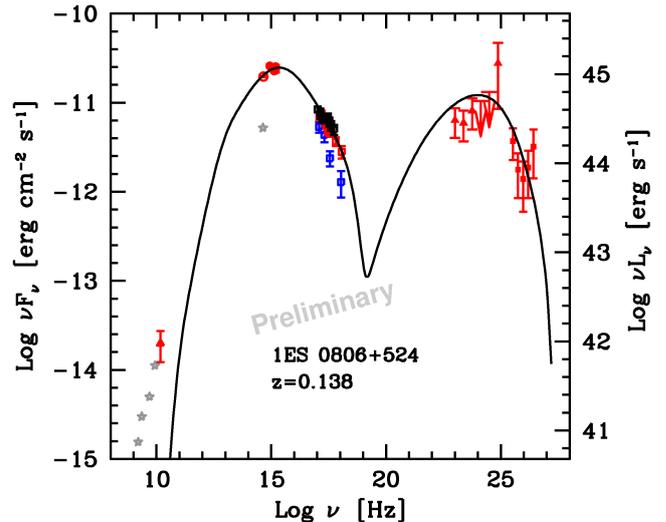
A one–zone SSC model can explain the spectral energy distributions obtained from the low and high state with parameters similar to those typically inferred for other HBL
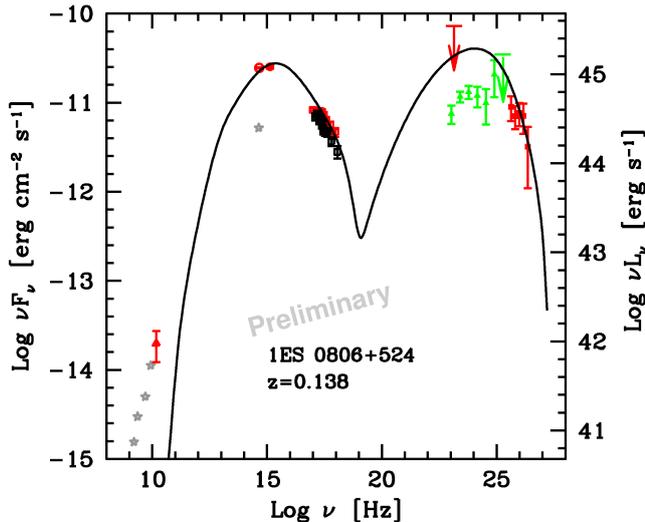
Fig. 2: SED of the high state activity of 1ES 0806+524 on February 24th. MAGIC VHE γ-ray data was corrected for EBL absorption [17] (red, blank squares). We show the *Fermi*-LAT upper limit from February 24th (red arrow) next to an averaged spectrum (green, filled triangles) derived from November 2010 until June 2011. Simultaneous and quasi–simultaneous data from February 27th and March 1st are provided by *Swift*/XRT/UVOT in X-rays (black and red, filled squares) and the U–band (red, filled circles), optical data in the R–band from KVA (red, blank circle) and radio data from the OVRO telescope (red, blank triangle). Archival radio and optical data (gray, blank stars) from NED are also shown. The solid line represents the fit with a one–zone SSC–model (Table 1).

Fig. 3: Same as Figure 2, but for the low state activity of 1ES 0806+524. The HE γ-ray spectrum is been dervied from *Fermi*-LAT observations carried out from January to March 2nd, 2011, excluding the night of the VHE γ-ray flare. The simultaneous and quasi–simultaneous data from *Swift*/XRT/UVOT in X-rays is divided as follows: blue, filled squares correspond to observations from February 1st, while observations from February 28th and March 1st are indicated in red and black (due to exact superimposition, data from February 25th and 27th are not visible). Red, filled circles in the U–band denote observations from February 1st to March 1st.

objects. According to the model, during the high VHE state, the power in electrons and protons increased while the magnetic energy density decreased. The high state SED indicates a mild inverse Compton dominance.

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