Multi-wavelength Observations of the HBL 1ES 1011+496 in Spring 2008

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Abstract. In the spring of 2008 MAGIC organised multi-wavelength (MWL) observations of the blazar 1ES 1011+496. 1ES 1011+496 is a high-frequency peaked BL Lac object (HBL) discovered at VHE γ-rays by MAGIC in spring 2007 during an optical outburst reported by the Tuorla Blazar Monitoring Programme. MAGIC re-observed the source during the 2008 MWL campaign which also included the Metsähovi, KVA, Swift and AGILE telescopes. This was the first MWL campaign on this source that also included VHE coverage. MAGIC observed 1ES 1011+496 from March 4th to May 24th 2008 for a total of 27.9 hours, of which 20 h remained after quality cuts. The observations resulted in a detection of the source at ∼7 σ significance level with a mean flux and spectral index similar to those during the discovery.

Here we will present the results of the MAGIC observations of the source in combination with contemporaneous observations at other wavelengths (radio, optical, X-rays, high energy γ-rays) and discuss their implications on the modelling of the spectral energy distribution.

Keywords: AGNs, BL Lac objects, 1ES 1011+964, multi-wavelength campaigns, VHE γ-rays, MAGIC

1. Introduction
Blazars are an extreme class of Active Galactic Nuclei (AGN) in which the jet of relativistic particles – particles travelling at nearly the speed of light – originating from close to the central black hole is pointed close to our line of sight. This causes an apparent increase in the jet...
luminosity and a decrease in the variability time scales of the AGN core across all wavelengths due to relativistic beaming effects. Blazar emissions are dominated by non-thermal radiation and their spectral energy distributions (SED) are characterised by two broad peaks of which the lower energy one is believed to originate from synchrotron emission of charged particles in the jet. The higher energy peak is most commonly explained by inverse Compton scattering of either the synchrotron (synchrotron self Compton - SSC, see e.g. [1, 2]) or external (external Compton - EC, [3, 4]) seed photons by the electrons and positrons in the jet but hadronic models [5, 6] are also considered. Blazars are divided into flat spectrum radio quasars and BL Lacertae objects (see e.g. [7]). The latter are further subdivided into low-, intermediate- and high-frequency peaked BL Lac (LBL, IBL and HBL, respectively) objects according to the frequency of the first peak which in the case of HBLs is located in the UV to soft X-ray regime. The second peak in HBLs is located in the GeV to TeV range which makes them good candidates to detect very high energy (VHE, >100 GeV) gamma-rays from.

Blazars show variability in flux at all wavelengths as well as spectral shape on time scales ranging from months to a few minutes. Therefore, in order to shed light on the VHE emission mechanisms of blazars, simultaneous observations of these sources across multiple wavelengths are required. It is particularly important to study the connection between the variability between different wavebands. With the increased sensitivity of the latest generation of Imaging Atmospheric Cherenkov Telescopes (IACTs) such campaigns have become feasible for a larger number of sources. Three campaigns of this type were organised by MAGIC in 2008: one on 1ES 1011+496 described in this contribution and the other two on Mrk 180 and 1ES 2344+514.

1ES 1011+496 is an HBL located at a medium redshift of z=0.212. It was discovered at VHE by MAGIC in 2007 following an optical high state reported by the Tuorla Blazar Monitoring Programme [8]. Previous observations of this source at VHE showed only a hint of signal (see e.g. [9]) and the results presented here constitute the first follow-up detection of the source. The object shows frequent fluctuations in its optical brightness with the core flux increasing by up to a factor of ~2-3 over the lowest states during flares. It has also been observed in the X-rays by Einstein [10] and the Swift/XRT [11] telescopes always showing a steep spectrum. There was no definite detection by EGRET [12] but it has been clearly detected by Fermi and was included already in the Fermi 3-month catalogue. The Fermi observations showed a very hard γ-ray spectrum [11]. The MWL campaign was the first of its kind on this source.

2. Observation Campaign and Results
MAGIC (Major Atmospheric Gamma-ray Imaging Cherenkov) is a system of two 17 m IACTs located on the Canary island of La Palma, Spain at ~2200 m asl. At the time of the 2008 campaign the second telescope was still under construction and observations were carried out using only MAGIC-I which has been in operation since 2004. Thanks largely to its 236 m² reflective area MAGIC-I achieved an energy threshold of ~60 GeV (~30 GeV with a special trigger) – the lowest of any IACT. It reached a sensitivity of ~1.6% of Crab nebula flux (5 σ in 50 h) >200 GeV with an energy resolution of ~20-30% and an angular resolution of ~0.1° [13].

The MWL observations were centered around common observation windows of the AGILE [14] satellite and the MAGIC-I telescope in spring 2008. Optical coverage was provided by the KVA [15] telescope which is operated concurrently with the MAGIC telescopes. Observations in the radio were performed by the Metsähovi radio telescope [16] and in the X-rays by the Swift [17] satellite.

MAGIC was able to observe the object on 25 nights between March 4th and May 24th 2008. The observation period was plagued by poor weather conditions at La Palma with frequent clouds, rainfall, strong wind and calima towards the end of the observation window. Nevertheless 1 http://users.utu.fi/kani/1m
a total of 27.9 hours of data was collected of which 8 hours had to be removed due to adverse weather conditions. The remaining 20 hours were not or only marginally affected by bad weather and survived the quality cuts. The observations were done in wobble mode between zenith angles of 20° and 37° and the data was analysed using the MAGIC standard analysis (for a comprehensive overview see e.g. [13]). The cut on $\alpha$ ($\leq$ 8 deg) to determine the significance of the signal and the number of excess events was optimised on Crab data from the same period. The MAGIC observations resulted in the detection of 398 events over 2070 background events in the signal region corresponding to a significance of the excess of 7.29 standard deviations using equation (17) in [18]. This constitutes the first confirmation of the source as a VHE emitter (see Figure 1). The energy threshold of this analysis was $\sim 150$ GeV which allowed for signal extraction down to about 100 GeV (see figure 2).

3. Discussion
The MAGIC observations showed a mean flux level similar to that measured during the discovery in 2007 [8]. Also the derived spectrum was compatible within the error bars although weak indications for a spectral hardening in 2008 were seen (see Figure 2).

The VHE $\gamma$-ray spectrum can be described by the simple power law (with the differential...
flux given in units of TeV$^{-1}$m$^{-2}$s$^{-1}$):

$$\frac{dN}{dE} = (1.6 \pm 0.1) \times 10^{-10} \left(\frac{E}{200\text{ GeV}}\right)^{-3.20 \pm 0.58}$$

No significant variability of the VHE flux was detected during the campaign (see Figure 3). A constant fit to the data yielded a $\chi^2$/d.o.f. of 13.9/18, corresponding to a probability of 73%. Nevertheless in one night (MJD 54561.9) a flux has been found which is >4 sigma off the fit line.

Of the other telescopes Metsähovi and AGILE did not detect the source within the given time windows. In the optical R band the source was at a relatively low state for most of the time with a major flare occurring at the end of the observation period. From the end of April to the beginning of May the source was also observed in the optical V and B band. The fluxes in these bands followed the same trends as in the R-band. In the X-rays a flare could be clearly detected as can be seen in the light curve in Figure 3. The observation sampling prevented to define a baseline flux level, therefore the rise and fall times of the flare could not be evaluated. The Swift UVOT data are still being analysed.

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**Figure 3.** The MWL light curve of 1ES 1011+496 with daily binning. The optical data (including the B and V band) are from the KVA telescope and are not host-galaxy corrected. In the MAGIC data, for points consistent with zero flux 99.7% upper limits are shown and the grey horizontal line denotes a constant fit to the data points. The full circles are the significant data points while the open ones represent fluxes consistent with zero but with significance >0.

**Figure 4.** A zoom into the MWL light curve around the second AGILE window. The same properties apply to the data points as in Figure 3. A 'high' and 'low' state has been defined according to the X-ray flux level which are used to compose simultaneous SEDs (see Figure 5).
There does not appear to be any obvious connection between the optical and X-ray, X-ray and VHE or optical and VHE light curves (see Figure 4). However the statistics of the individual data points of the VHE light curve are too low to draw definitive conclusions.

Two separate data sets, 'high' and 'low', defined according to the X-ray flux state of the source as can be seen in Figure 4, were used to construct a simultaneous SED (see Figure 5). Due to the small second observation window, no AGILE upper limit could be extracted for this period. The data has been modelled using a one-zone SSC model. The small difference between the SEDs of the low and high X-ray flux states does not make a dedicated modelling of both seem meaningful. Therefore, only one model fit was applied to the data for the time being.

The model assumes an emission region characterised by its radius R, magnetic field B and Doppler factor δ containing an electron population. The electrons with density K (defined at γ = 1) with which they are injected into the acceleration region follow a broken power law distribution with index e₁ for γ < γ_min < γ < γ_break and e₂ for γ_break < γ < γ_max. The spectral indices and power law slopes are derived then self-consistently from cooling and acceleration processes. The model parameters are given in table 1 and the results represent standard values for HBLs. The model fits the data rather well indicating that SSC mechanisms are the likely explanation for the observed emission.

Note that even though the Fermi bow-tie was not measured simultaneously to the other data it still fits relatively well into the applied model scenario. Taking into account that also the VHE spectrum seems not to have changed considerably from the time of the discovery to these observations, 1ES 1011+496 seems to show a rather constant emission at gamma-ray energies. At the lower energies, however, the average optical flux of ∼2.8 mJy from the core was ≈ 40% lower than the one measured during the discovery and equal to the one measured during the 2006 MAGIC observations. The X-ray flux was measured at almost 10x higher level than the one derived from archival observations in the VHE discovery paper. The low (non-simultaneous) X-ray flux constraining the SED modelling led [8] to the conclusion that in this

Table 1. Model parameters resulting from the modelling. See text for details.

| B [G] | δ    | R [cm] | K [cm⁻³] | e₁   | e₂   | γ_min | γ_break | γ_max |
|-------|------|--------|---------|------|------|-------|---------|-------|
| 0.19  | 25   | 1.0E+16| 6.6E+03 | 2.0  | 4.1  | 1     | 4.0E+04 | 6.0E+05 |

Figure 5. MWL SED of 1ES 1011+496. The 'high' and 'low' data correspond to the observation times defined in Fig 4. The KVA data are host-galaxy corrected following [20]. The Fermi bow-tie deduced from the LAT 1-year Catalog [21] is added for illustrative purposes. The MAGIC data have been corrected for EBL absorption using [22].
source, the inverse-Compton component would dominate over the synchrotron component. On the contrary, the simultaneous SEDs from these observations indicate that this interpretation may not be true, corroborating that this source is synchrotron dominated like most HBLs.

4. Conclusion
We organised the first MWL campaign including VHE coverage on the HBL 1ES 1011+496. The campaign resulted in the first confirmation of the source at VHE at a flux level similar to that measured during the discovery and a hint of hardening of the VHE spectrum compared to the discovery. The VHE flux was consistent with being constant, though significant variability in both the optical and X-ray wavelengths was detected. No apparent correlation between the flux levels in different wavebands was found. The data was modelled with a one-zone SSC model utilising typical parameters for BL Lac objects. The model provides a good fit to the available spectral data indicating that this scenario is sufficient to describe the emission mechanisms of the source. However data analysis and more refined modelling is still ongoing.

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