AGN Observations with the MAGIC Telescope

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MAGIC is presently the imaging atmospheric Cherenkov telescope with the largest reflecting surface and the lowest energy threshold. MAGIC concluded its first year of regular observation in April 2006. During this period and the preceding commissioning phase, 25 Active Galactic Nuclei have been observed and VHE $\gamma$-ray emission has been confirmed by 4 of them. Two more AGNs have been detected as $\gamma$-ray sources with high statistical significance for the first time. We report in this paper the results obtained analyzing data of the detected sources. Temporal and spectral properties of detected signals are shown and discussed.

**Keywords**: AGN, Blazars, TeV $\gamma$-ray astrophysics, Cherenkov Telescope

1. Introduction

MAGIC (Major Atmospheric Gamma Imaging Cherenkov) telescope,$^{1,2}$ located on the Canary Island La Palma (2200 m a.s.l., 28.4’N, 17.54’W), is currently the largest imaging air Cherenkov telescope in operation. The MAGIC construction was completed in Fall 2003 and after a commissioning phase of about one year MAGIC started its first regular observation cycle in April 2005. According to detailed simulation of atmospheric showers and detector response the trigger threshold is around 60 GeV for low zenith angle observations$^3$ while the analysis threshold is about $E_{Th} = 100$ GeV in the same conditions. MAGIC integral flux sensitivity has been calculated from Monte Carlo simulation and results in about 5% of $\Phi_{Crab}$ at $E > 100$ GeV and 2% of $\Phi_{Crab}$ at $E > 1$ TeV.$^3$ The angular resolution has been estimated applying the DISP method to Crab data and results in about 0.1° for $\gamma$-ray events with $E > 200$ GeV.$^4$ The accuracy in the determination of the point-source position improves as the square root of the number of collected events and is ultimately limited by tracking accuracy.
(≈ 0.02°). The energy resolution has been estimated from Monte Carlo data and results in \( \Delta E/E ≃ 30\% \) at \( E = 100 \text{ GeV} \) and \( \Delta E/E ≃ 20\% \) for \( E > 1 \text{ TeV} \). The systematic errors on the measured flux were estimated to be around 50\% for the absolute flux level and 0.2 for the spectral index.

2. Observed Blazars

MAGIC, during its first year of regular data taking, observed a sample of Blazars, mainly HBLs, at redshifts \( z < 0.3 \). This sample was chosen selecting northern Blazars with the highest expected VHE (here defined as \( E > 100 \text{ GeV} \)) fluxes according to leptonic and hadronic models of \( \gamma \)-ray emission. Moreover, considering possible correlations between VHE emission and optical/X-ray emission, MAGIC performed Target of Opportunity observations whenever alerted by optical/X-ray telescopes. We present here the spectral properties and the temporal behavior of the detected sources: Mkn 421, Mkn 501, Mkn 180, 1ES1959+650, 1ES1218+304 and PG1553+113.

2.1. Markarian 421

Mkn 421 (redshift \( z = 0.030 \)) was the first extragalactic VHE \( \gamma \)-ray source detected by Whipple\(^7\) in 1992. Many observations of this source were performed since then showing flux variations larger than one order of magnitude and flares with doubling times as short as 15 minutes.\(^8\) A significant correlation between X-ray and \( \gamma \)-ray flux has been detected during multi wavelength campaigns involving Cherenkov telescopes and X-ray detectors.\(^9\)

![Fig. 1. Light curve for Mkn 421 from November 2004 to April 2005. Each data point is the nightly averaged integral flux above 200 GeV. Left panel: data from November 2004 to January 2005. Right panel: data for April 2005.](image)

MAGIC observed Mkn 421 for 19 nights and an overall observation time of 15.5 hours. All the data were taken at zenith angle below (30°) with the only exception of 1.5 hours taken in December 2005 at 42° < \( \text{ZA} < 55° \) during simultaneous observations with H.E.S.S.\(^1\)
During MAGIC observations Mkn 421 flux above 200 GeV ranged from 0.5 to 2 Crab units (see Fig. 1). Significant flux variations up to a factor four overall and up to a factor two between successive nights can be seen. A clear correlation between the X-ray flux, measured by the All-Sky-Monitor onboard the RXTE satellite, and the VHE \( \gamma \)-ray flux measured by MAGIC can be seen in Fig. 2. The energy density distribution of gammas from Mkn 421, that is the differential photon spectra multiplied by \( E^2 \), is shown in Fig. 3 both for the measured spectrum and the de-absorbed one (i.e. corrected for the effect of extragalactic absorption). The de-absorbed spectrum is curved, clearly indicating that the curvature in the measured spectrum is not caused by the absorption of the VHE \( \gamma \)-rays by the EBL photons but has an intrinsic origin. For further details about Mkn 421 data analysis see.\textsuperscript{12}

### 2.2. Markarian 501

Fig. 4. Light curve for Mkn 501 from June to July 2005. Each data point is the night averaged integral flux above 200 GeV.
Mkn 501 (redshift $z = 0.034$) was the second extragalactic VHE $\gamma$-ray source discovered by Whipple$^{13}$ in 1996. Following observations in 1997 showed that Mkn 501 integral flux above 1 TeV can reach 10 Crab units$^{14}$ and can drastically change on timescales of 0.5 days.

MAGIC observed Mkn 501 between June and July 2005 for a total of 24 nights and 32.2 hours of observation time. Mkn 501 was in a rather low flux state (integral flux above 200 GeV around 0.4 Crab units) when MAGIC started its observation. Suddenly, on 30th Jun, its flux reached 4 Crab units, see Fig. 4. This flare stimulated further observations which were performed in the following days also in the presence of moonshine to extend the time coverage. The source was found in high state (integral flux above 2 Crab units) on two more nights. In particular a flare with doubling time as short as 5 minutes or less was detected on the night of 10th July 2005, see the inlay in Fig. 5. The high source flux together with the MAGIC high sensitivity allowed the measurement of the source spectrum in time intervals as short as 10 minutes. A significant hardening of the spectrum as the flux grows was found, confirming previous indications by Whipple.$^{13}$ It is worth noticing that this is the first time that spectral hardening has been measured on time scales of $\sim$ 10 minutes. A detailed publication on the results of the Mkn 501 data analysis is in preparation.

2.3. Markarian 180

Mkn 180 (1ES1133+704) at redshift $z = 0.045$ is the second extragalactic $\gamma$-ray source discovered by MAGIC. Previously this source had been observed by HEGRA and Whipple collaborations but these observations resulted
only in upper limits on the VHE \(\gamma\)-ray flux.\textsuperscript{15,16} MAGIC observed Mkn 180 for 9 nights after an alert received by the KVA telescope, on 23rd March 23 2006. In the following nights MAGIC observed this source for 14.4 hours. Only 11.1 hours survived to the quality cuts applied to remove runs with unusual trigger rate, usually related to not optimal atmospheric conditions. This sample was enough to find a clear signal at 6.5\(\sigma\) level with 271 excess events and to measure the integral flux above 200 GeV, \(\Phi(E > 200\text{GeV}) = (2.3 \pm 0.7) \times 10^{-7} \text{m}^{-2} \text{s}^{-1}\), which corresponds to 10\% of the Crab Nebula flux as measured by MAGIC. No evidence of flux variation was found on a daily scale. The differential energy distribution, shown in figure\textsuperscript{7} with filled

![Differential energy spectrum of Mkn 180, measured by MAGIC (full circles) and corrected for the effect of extragalactic absorption (open circles). The black line represents a power-law fit to the measured spectrum. The fit parameters are listed in the figure. For comparison, the Crab Nebula spectrum measured by MAGIC is also shown (dotted line).](image)

points, can be fitted by a power law with spectral index \(\alpha = 4.2 \pm 0.7\). In the same figure also the de-absorbed spectrum (i.e. corrected for the effect of the extragalactic absorption) is shown (open circles). For further details on this analysis see.\textsuperscript{17}

### 2.4. 1ES1959+650

The first hint of VHE \(\gamma\)-ray emission from 1ES1959+650 (\(z = 0.047\)) was claimed by the Seven Telescope Array collaboration in 1998.\textsuperscript{18} This claim was later confirmed both by Whipple and HEGRA collaborations\textsuperscript{19,20} which observed this source in May 2002 when its X-ray flux was much higher than
the usual level. During observations in 2002 a so-called *orphan flare*, i.e. a VHE $\gamma$-ray activity in the absence of high activity in X-rays, was observed. Orphan flares are very interesting because they could be an indication of hadronic acceleration in Blazars. They are not expected, in fact, within the SSC model. MAGIC observed 1ES1959+650 when it was still in the commissioning phase, therefore not at its best performances. Nevertheless a clear signal at $8.2\sigma$ significance level was found and the energy spectrum was measured down to 180 GeV for the first time. The energy spectrum between 180 GeV and 2 TeV can be well fitted with a power law with a photon index $\alpha = 2.72 \pm 0.14$ and is consistent with the one measured by HEGRA.\textsuperscript{20} see Fig. 6 The integral VHE $\gamma$-ray flux above 180 GeV resulted in $(3.73 \pm 0.41) \times 10^{-7} \text{m}^{-2}\text{s}^{-1}$, in agreement with the low state flux measured by HEGRA. For further details of the analysis of these data and its results see.\textsuperscript{21}

2.5. **1ES1218+304**

The Blazar 1ES1218+304 at redshift $z = 0.182$ is the first extragalactic VHE $\gamma$-ray source discovered by MAGIC. This source has been observed by Whipple since the discovery of Mkn 501 but these observations leaded only to an upper limit on the VHE flux.\textsuperscript{22} HEGRA collaboration also observed this source, but again no detection was claimed and only an upper limit on the $\gamma$-ray flux was published.\textsuperscript{23}

![Fig. 8. Differential energy spectrum of 1ES1218+304. The upper limits correspond to 90% confidence level. The grey-shaded region shows the systematic error due to initial MC spectrum analysis cuts.](image1)

![Fig. 9. Differential energy spectrum of PG1553+113 as derived from the combined 2005 and 2006 data. The grey-shaded region shows the systematic error due to initial MC spectrum and analysis cuts.](image2)

MAGIC observed 1ES1218+304 for 8.2 hours during seven nights in January 2005. An excess of 560 events with statistical significance of $6.4\sigma$ was found. The night-by-night $\gamma$-ray light curve didn’t show any statistically
significant variations. The energy spectrum between 80 GeV and 600 GeV can be well fitted by a power law with photon index $\alpha = 3.0 \pm 0.4$. The integral flux above 100 GeV is $\Phi(E > 100\text{GeV}) = (8.7 \pm 1.4) \times 10^7 \text{m}^{-2}\text{s}^{-1}$ and is below the upper limits at higher energies determined in the past. For details about these data analysis see.\textsuperscript{24}

2.6. \textit{PG1553+113}

The first evidence of VHE $\gamma$-ray emission from PG1553+113 (redshift unknown, $z > 0.09$) was claimed in 2005 by H.E.S.S. collaboration showing an excess at $4\sigma$ level.\textsuperscript{26} MAGIC started to observe this source in 2005 and, motivated by a strong hint of signal in the 2005 data, continued in 2006 for an overall observation time of 18.8 hours. A very clear signal was detected with a significance of $8.8\sigma$. There is no evidence of $\gamma$-rays short term variability, but a factor of three change in the flux level from 2005 to 2006 was found. The combined 2005 and 2006 differential energy spectrum for PG1553+113 is well described by a pure power law with a photon index $\alpha = 4.2 \pm 0.4$, in good agreement with H.E.S.S. result in the overlapping energy range. For details of the analysis and results see.\textsuperscript{27}

3. Conclusions and Outlook

An overview of the extragalactic VHE $\gamma$-ray sources detected by MAGIC until May 2006 is given. In this period MAGIC detected VHE $\gamma$-ray emission by 6 extragalactic sources: Mkn 421, Mkn 501, Mkn 180, 1ES1959+650, 1ES1218+304 and PG1553+113. Two of them, 1ES1218+304 and Mkn 180, have been discovered by MAGIC while PG 1553+113 has been confirmed as $\gamma$-ray source at high significance level after the first hint of signal by H.E.S.S. The energy spectrum of Mkn 421 has been measured down to 100 GeV for the first time showing a de-absorbed spectrum which clearly flattens toward 100 GeV. Mkn 501 has been caught in flaring states in 3 nights with flux higher than 2 Crab units. Flux doubling time down to 5 minutes has been observed and spectral hardening as the flux increases has been measured on 10 minutes time scale. Gamma-ray emission from Mkn 180 has been discovered during an optical outburst indicating a possible correlation between $\gamma$-ray and optical emission. The energy spectrum of 1ES1959+650 has been measured down to 180 GeV, well below previous measurements by HEGRA, when the source was in a low activity state.

Re-observations of the presented sources as well as the analyses of further observed Blazars are ongoing.
Collaborations with observatories in other spectral ranges have proved to be very fruitful and will be extended and strengthened in the near future.

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References

5. B. Riegel et al., In Proc. 29th Int. Cosmic Ray Conf. (Pune), 5, 359 (2005)