Recent results from MAGIC observations of AGN

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Abstract. MAGIC is a system of two 17m Cherenkov telescopes, sensitive to very high energy (VHE) gamma-rays between 50 GeV up to several tens of TeV. MAGIC observations of Active Galactic Nuclei (AGN) have resulted in the discovery of many previously unknown VHE gamma-ray emitting sources adding also new source types to the list of extragalactic gamma-ray emitters as well as new constraints for the emission models. Many of the discoveries have been triggered by the optical high state of the source as reported by the Tuorla blazar monitoring program, in several cases the targets were also listed as promising candidates by the Fermi collaboration based on their flux and spectrum. In this contribution I discuss the new discoveries as well as the new constraints for emission models of AGN derived from recent MAGIC observations.

1. Introduction
MAGIC is a system of two 17 meters Cherenkov Telescopes located in Observatorio del Roque de los Muchachos on La Palma, 2200 m above sea level. MAGIC-I has been in operation since 2004 and the stereoscopic system has been operation since 2009. MAGIC has an enhanced duty cycle $\sim 20\%$ as it is able to operate in presence of moderate moonlight and twilight.

The performance of the MAGIC stereoscopic system is reported in [1]. The low energy threshold of 50 GeV (with special trigger 25 GeV) allows observations of the distant universe and overlaps with the Fermi satellite. Together with the improved sensitivity of stereoscopic system (E$>250$GeV 0.8% Crab in 50h), it has played a key role in most recent new VHE $\gamma$-ray emitting AGN discoveries.

The known extragalactic VHE $\gamma$-ray emitters are mostly active galactic nuclei (with the exception of two starburst galaxies, which are not discussed here) with relativistic jet. The most numerous subclass within the VHE $\gamma$-ray AGN are blazars, in which the relativistic jet points close to our line of sight. However, also a few non-blazar AGN have been detected in VHE $\gamma$-rays namely radiogalaxies M 87 [2] and Cen A [3] and the Perseus Cluster galaxies NGC 1275 and IC 310 [4, 5, 6].

The blazar class consists of two separate classes of AGN namely BL Lac objects and flat spectrum radio quasars (FSRQs). BL Lacs are more numerous in the class of VHE $\gamma$-ray emitting blazars ($>30$ known) and only three FSRQs have been detected. The VHE $\gamma$-ray emitting BL Lacs typically have their synchrotron peak in UV to X-ray energies and are therefore classified as high energy peaking BL Lacs. The second peak of the SED is then located at $>\text{GeV}$ energies, which makes them good candidates for sub-TeV and TeV emission. On the other hand some BL Lacs and all FSRQs have their first peak in optical regime, which makes the detection of VHE $\gamma$-rays from them less likely.

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The MAGIC extragalactic science program covers all the classes of VHE γ-ray emitting AGN. The observational strategies include systematic searches, target of opportunity observations, multiwavelength campaigns as well as monitoring of known sources. Target of opportunity observations are performed when a source is seen in a high state in optical (triggers from the Tuorla blazar monitoring program) or γ-ray (triggers from Fermi); this has proved to be more successful strategy than systematic searches (nine of the MAGIC discoveries have resulted from ToO, while three discoveries have been made in systematic searches). Target of Opportunity observations of known sources focus on the fast variability of the sources in VHE regime, as well as correlations between different wavebands, both of which puts severe constrains on the emission mechanism and emission region size. However, these questions are even better accessed with long-term multiwavelength monitoring of the strong sources, in which MAGIC is also participating.

In this contribution we give an overview of recent MAGIC AGN observations covering VHE detection of two FSRQs, which challenge the current canonical models for their emission, discoveries of new sources and finally results from multiwavelength campaigns and monitoring of known strong VHE γ-ray emitters.

2. Flat Spectrum Radio Quasars 3C 279 and PKS 1222+216
There are several scenarios for the γ-ray and VHE γ-ray emission in FSRQs. The emission can, in principle, be explained by both leptonic and hadronic models: the leptonic models traditionally rely on external Compton (EC, e.g. [7, 8]), invoking the inverse Compton scattering of external photons from accretion disk or broad line region (BLR) clouds [9, 10], while in the hadronic models [11, 12, 13] the VHE γ-ray photons are produced by proton initiated cascades or directly through proton synchrotron radiation.

The leptonic models are very sensitive to the site of the emission: the external Compton models relying on photons originating from broad line emission clouds are not efficient if the emitting blob is outside the BLR and in the SSC models the γ-ray emission must originate from a different emission region than the main component of the synchrotron radiation in order to reproduce the observed γ-ray flux [13]. It should also be noted, that independently of the emission mechanism, the internal absorption cannot be neglected if the emission region is located inside the BLR [14, 15]. In the case of external Compton the internal absorption combined with reduced efficiency of the IC scattering occurring in the KleinNishina (KN) regime [16] should produce a strong softening of the spectrum above few tens of GeV if the external photons derive from the BLR.
Figure 2. The light curves of 3C 279 in January 2007 from VHE γ-rays (MAGIC), X-rays (RXTE), optical (KVA) and infrared (REM). MAGIC detected > 5σ γ-ray excess from the source only on 16th of January (MJD 54116). For the MAGIC light curve the night by night flux is calculated assuming that 3C 279 always emits γ-rays above 150 GeV.

Alternatively, the emission can be produced in regions located far beyond the broad line region, at distances at which the dominant radiation field for EC is that of the parsec-scale dusty torus [17]. In this case, internal absorption can be neglected up to ~ 1 TeV but, due to the large size of the emission region, a minimum variability timescale of the order of ~1 day is expected.

MAGIC observations of 3C 279 and PKS 1222+216 have shed new light on the emission mechanism and site in these two well-known FSRQs.

3C 279 was the first flat-spectrum radio quasar (FSRQ) discovered to emit very high energy (VHE, defined here > 100 GeV) γ-rays [8]. With a redshift of 0.536, 3C 279 is also the most distant of the VHE γ-ray emitting sources discovered so far. The source was re-observed by MAGIC-I (for performance see [18]) in January 2007 during a major optical flare and from December 2008 to April 2009 following an alert from the Fermi space telescope on an exceptionally high γ-ray state. In January 2007 it was observed for a total of 23.6 h, 18.6 h (seven nights) of which passed the quality selection. In December 2008 to April 2009 a total observation time of 28.1 h was accumulated over 20 days. Only one night, MJD 54116 (January 16, 2007), revealed a significant excess in the MAGIC data after off-subtraction, the significance of the excess is 5.6σ (pre-trial). The VHE γ-ray spectrum of the flare can be described by a simple power law (with the differential flux given in units of TeV$^{-1}$ m$^{-2}$ s$^{-1}$):

$$\frac{dF}{dE} = (5.7 \pm 1.3) \times 10^{-7} \left(\frac{E}{300 \text{ GeV}}\right)^{-3.1\pm1.1}$$

(1)

The highest spectral energy point has a mean energy of 350 GeV. Flux and spectral index are comparable with the 2006 detection.
Figure 3. The spectral energy distribution of 3C 279 on January 2007 16th (MJD 54116). The red symbols show the REM (MJD 54114.4, triangles), KVA (filled circle), RXTE (bow-tie) and MAGIC (deabsorbed, triangles) data used to fit the two-zone model (see [8]). Blue line shows the emission from the zone inside BLR and red line the emission from outside the BLR. Additionally REM data from MJD 54113.3 (Maximum of the REM lightcurve) cyan and MJD 54117.3 (black) are shown. The dashed lines correspond to blackbody radiation from the IR torus (red) and BLR (blue). For comparison also historical data are shown: 1991 high state (gray: [19]), 1993 low state [20] (green: Maraschi et al. 1994) 1996 high state (orange, blue bow-tie: [21, 22]) and 2003 low state (magenta: [23]).

Figure 4. The observed spectral energy distribution of 16th of January 2007 modeled with the lepto-hadronic model. The data used for fit are the same as in Figure 3. The overall fit is shown with a red line with the following components at high energies: the synchrotron radiation of pair creation electrons and positrons cascaded down from the optically thick regime (magenta dotted line), synchrotron radiation from positrons from the pion decay (green dashed line), synchrotron radiation from electrons from the pion decay (blue dashed line), inverse Compton scattering (cyan dot dashed line) and proton synchrotron emission (black double dashed line). The VHE $\gamma$-ray emission is mostly the sum of the three first components while in X-rays the main contribution comes from the inverse Compton scattering (like in the purely leptonic models). The low energy bump is produced by the electron synchrotron radiation.

There is multiwavelength data from radio to X-rays available for both observing periods. The MAGIC detection took place in the decay phase of the optical-IR and X-ray flare (see Fig.2). Larionov et al. [24] associate the optical flare with a VLBA component emerging from the core at MJD 54063$\pm$40 based on simultaneous $\sim$300 degree rotation of the optical and VLBA 43 GHz core polarization angle. If the VHE $\gamma$-ray emission is connected to the optical flare -which in turn appears connected to the radio flare- this would also place the emission region of the VHE $\gamma$-ray flare far out in the jet.

The spectral energy distribution (SED) is difficult to reproduce with traditional one-zone SSC-EC model, because it largely overproduces the MeV emission (although there is no
simultaneous measurements from this energy regime the required MeV flux would be \( \sim 10 \) higher than the historical maximum observed from the source. The SED is better reproduced by a two zone SSC-EC model (Fig.3), where the optical to X-ray emission zone is located inside the BLR, and the VHE \( \gamma \)-ray emission outside the BLR where soft photons from the infra-red torus serve as seed photons for Inverse Compton scattering. The SED can also be reasonably well reproduced by a hadronic model (Figure 4). The observations, results and modeling are described in detail in [25].

PKS 1222+21 \((z=0.432)\) is a \( \gamma \)-ray blazar [26] with a relatively hard spectrum in the GeV range and has been included in the list of \( > 100 \) GeV emitters in the analysis of [27]. It is characterized by highly superluminal jet knots with apparent velocity up to \( 21c \) [28]. On June 17, 2010, PKS 1222+21 was observed with the MAGIC telescopes for \( \sim 0.5 \) hr (MJD 55364.908 to MJD 55364.931), in the so-called wobble mode. These observations yield an excess corresponding to a statistical significance of \( 10.2\sigma \).

The observed VHE and GeV (from simultaneous Fermi observations) \( \gamma \)-ray spectra are consistent with a single powerlaw with index \( \sim 2.7 \pm 0.3 \). This suggests that the 100 MeV-400 GeV emission originates from one single component, which must be located outside the BLR as no strong softening is seen. This result is discussed in detail in [29] and Becerra-González et al. 2011 (this volume).

3. New Discoveries
The number of known extragalactic \( \gamma \)-ray emitters has been increasing by \( \sim 5-10 \) sources per year since the current generation of instruments came online. Currently the number of known sources is 45\(^1\). To search for new VHE \( \gamma \)-ray emitting AGN MAGIC has been observing a sample of X-ray bright AGN [30, 31], but also performing target of opportunity observations of AGN that are in high state in optical as reported by the Tuorla blazar monitoring program \(^2\). In addition Fermi collaboration has been providing lists of candidate TeV blazars, based on the observation of \( > 50 \) GeV photons from the sources, to the IACT community; observations of these sources have resulted in many new discoveries: already 9 sources from the lists have been discovered to emit VHE \( \gamma \)-rays.

3.1. Optically Triggered Discoveries
The Tuorla blazar monitoring program was started in 2002 with a goal to study the optical variability of TeV candidate blazars from [32]. Since the beginning of the science observations of MAGIC, the optical lightcurves have been used to trigger Target of Opportunity observations. This has resulted in several discoveries: Mrk 180 [33], 1ES 1011+496 [34], S5 0716+714 [35] and most recently B3 2247+381 [36] and 1ES 1215+303 [37].

B3 2247+381 \((z= 0.119)\) was previously observed by MAGIC telescope as a part of the systematic search of VHE \( \gamma \)-rays from X-ray bright BL Lac objects [31]. The source was selected from the Nieppola et al. [38] sample with reported X-ray flux > 2 mJy. They classify the source as an intermediate peaking BL Lac object, while in [39] it is classified as high peaking and the reported X-ray flux is \( F(>1 \text{ keV}) \) 0.6 mJy. MAGIC observed the source in August-September 2006 and these observations resulted in an upperlimit \( F(> 140 \text{ GeV}) < 1.6 \times 10^{-11} \text{cm}^{-2}\text{s}^{-1} \). The source has been monitored in optical by Tuorla blazar monitoring program ever since. In autumn of 2010 the source was observed in a high optical state (brightening of the core \( > 50\% \), see Reinthal et al. this volume), which triggered MAGIC observations. MAGIC observed the source during 13 nights between September 30th, and October 30th 2010, collecting a total of

\(^1\) http://www.mppmu.mpg.de/~rwagner/sources

\(^2\) http://users.utu.fi/kani/1m
21.2 hours of data, of which only 2.9 hours were discarded. The source was detected at the 5.6σ level. This is the first detection of the source in VHE γ-rays.

1ES 1215+303 (also known as ON 325) is a high energy peaking BL Lac object with uncertain redshift (two values can be found in the literature: \( z=0.130 \) and \( z=0.237 \)). The source was classified as a promising candidate TeV blazar by [32] and has been observed several times in VHE γ-rays prior to the observations presented here (e.g. [31]). The source was also in the Fermi bright AGN catalog [40] showing variable flux and hard spectra (\( \Gamma = 1.89 \pm 0.06 \)). In January 2011 the source was in a high state in optical, which triggered MAGIC observations in January-February 2011 for a total \( \sim 20 \) hours. The observations were made in the so called wobble mode in dark night and moderate moon conditions. The data were taken at zenith angles from 1 to 40 degrees. The source was clearly detected at 10σ level, the first significant detection of VHE γ-rays from 1ES 1215+303.

Multiwavelength data simultaneous and quasi-simultaneous to MAGIC observations of these two blazars were collected from radio to γ-ray frequencies including e.g. Metsähovi 37 GHz data (1ES 1215+303 only), optical, Swift and Fermi data. The analysis and interpretation of these data are ongoing and dedicated publications in preparation.

3.2. Fermi Candidate Discoveries

The Fermi Space Telescope has detected 698 γ-ray emitting AGN above energies 100 MeV [26]. Some of these AGN are also observed to emit photons above \( > 30 \) GeV and are therefore considered to be good candidates for ground based γ-ray observations. In October 2009 the Fermi collaboration distributed the list of such VHE candidate sources to all the IACTs (Fermi Collaboration priv. comm.) with a goal of further increasing the number of extragalactic VHE γ-ray emitters. The second edition of this list was released in October 2010. MAGIC has observed a few of the most promising candidates from these lists (and it should be noted that both latest optically triggered discoveries were also in Fermi lists).

In July 2010 MAGIC announced the discovery of Very High Energy (VHE; \( > 100 \) GeV) γ-ray emission from the source MAGIC J2001+435 [41], which is positionally consistent with the Fermi-LAT γ-ray source 1FGL J2001.1+4351, and the radio source MG4 J200112+4352, recently identified with a BL Lac object [42]. The preliminary analysis of the MAGIC data using the standard cuts optimized for soft energy spectra yielded a detection of \( \sim 120 \) γ-rays, corresponding to a pre-trail statistical significance of \( \sim 7 \) standard deviations. The observed flux is estimated to be \( \sim 20\% \) of the Crab nebula flux above 100 GeV. The dedicated publication is in preparation.

In October 2010 MAGIC also reported the discovery of VHE γ-rays from the central galaxy of the Perseus cluster, NGC 1275 [4]. The MAGIC observations were carried out in stereoscopic mode starting in August 2010 and the preliminary analysis shows an excess at the 5σ level. Dedicated publication is in preparation. In the same field of view MAGIC also observed VHE γ-ray emission from another Fermi detected [5] Persues cluster galaxy IC 310 [6].

4. Multiwavelength campaigns and multiwavelength monitoring

Longterm multiwavelength monitoring is the best tool for studying the emission mechanisms and emission sites in AGN. However, it is difficult to organize and in many cases fixed window multiwavelength campaigns are the only viable option. MAGIC participates in long-term MWL monitoring (Mrk 421, Mrk 501 and M 87) and is also organizing fixed time multiwavelength campaigns together with other instruments.

In 2008 MAGIC organized several fixed time multiwavelength campaigns: 1ES 1011+496, Mrk 180 and 1ES 2344+514 were observed in radio, optical, X-ray, γ-rays and VHE γ-rays. For 1ES 1011+496 and Mrk 180 these observations were the first follow-up observations at VHE γ-rays after the discovery and the first MWL observations of the sources. 1ES 1011+496 was
observed in a similar VHE γ-ray flux level (Reinthal et al. this volume) as during the discovery.
Mrk 180 was observed in a very variable X-ray state, while 1ES 2344+514 was in a very low state in all wavebands during the campaign resulting only in marginal detection of the source by MAGIC. Detailed publications on these campaigns are in preparation.

MAGIC has been monitoring the strong VHE γ-ray blazars Mrk 421, Mrk 501 and 1ES 1959+650 since the beginning of its science operations (e.g. [43]). After the launch of the Fermi satellite, which operates in survey mode, the sources have been constantly observed in γ-ray energies >100 MeV. This allows for the first time simultaneous observations covering all of the high energy peak. Since 2009 there has been intense MWL monitoring campaigns (led by the Fermi collaboration) on Mrk 421 and Mrk 501, where the sources are observed every second day from radio to VHE γ-ray energies. The campaigns have duration of 4.5 months covering basically all of the time window when these sources are observable from earth based observatories. MAGIC has been participating in these campaigns along with Swift, RXTE, GASP-WEBT, F-GAMMA and VLBA. The results of the 2009 campaigns were recently published [44, 45]. Mrk 421 was in a low emission state, showing low flux and low multifrequency variability. The spectral energy distribution (Fig.5) is well reproduced with a leptonic (one-zone Synchrotron Self-Compton) or a hadronic model (Synchrotron Proton Blazar). Instead Mrk 501 was showing large variability during the 2009 campaign, but MAGIC observations were conducted mainly in the low state. The average spectral energy distribution of Mrk 501 is well described by the standard one-zone synchrotron self-Compton (SSC) model (Fig.6). MAGIC also participated in the 2010 and 2011 campaigns.

![Figure 5.](image1.png)
**Figure 5.** Spectral energy distribution of Mrk 501 averaged over all observations taken during the multifrequency campaign performed between March 15, 2009 and August 1, 2009.

![Figure 6.](image2.png)
**Figure 6.** Spectral energy distribution of Mrk 421 averaged over all the observations taken during the multifrequency campaign from January 19, 2009 to June 1, 2009.

M 87 is a giant elliptical radio galaxy situated in the Virgo cluster at a distance of 16.7 Mpc. M 87 has been observed by MAGIC since 2005 and since 2008 MAGIC, HESS and VERITAS have been monitoring the source jointly allowing better sampling of the VHE γ-ray lightcurve. VHE γ-ray emission shows day-scale variability, which excludes many of suggested emission scenarios and puts strong limits on the size of the emission region [46, 47]. M 87 is also monitored by Chandra (X-rays), HST (optical) and VLBA. The vicinity of M 87 allows to distinguish different parts of the jet (especially the core and the component called HST-I) in these energy intervals and therefore study the location of the emission regions in the jet. This combined with the VHE γ-ray monitoring gives a direct view of the emission site of VHE γ-rays in the jet, which was demonstrated by the 2007-2008 joint campaign [48]. MAGIC also participated in 2009, 2010 and 2011 campaigns (see Raue et al. this volume).
5. Summary and Conclusions

The MAGIC AGN observation program currently consists of long-term monitoring of known strong VHE γ-ray emitters, fixed term multiwavelength observations, targeted observations of good TeV candidate sources and target of opportunity observations. In past years the long-term monitoring has also been combined with the data from other wavelengths, which allows us to study correlations between different energy intervals and put constraints on emission mechanisms in work. However, the number of sources we can detect with short observations in low state is very limited and for many sources it is more efficient to trigger MAGIC observations when the source is in a high state in optical and γ-ray. Target of opportunity observations of known VHE γ-ray emitters (e.g. 3C 279 in 2007 optical trigger, 1ES 0806+524 in 2011 optical trigger) have resulted in the detection of short term variability in these sources. Target of opportunity observations have also resulted in the discovery of new VHE γ-ray emitting blazars (e.g. PKS1222+21 in 2010 γ-ray trigger, B3 2247+381 in 2010 optical trigger, 1ES 1215+303 in 2011 optical trigger). Also targeted observations have resulted in new detections (MAGIC J2001+435 and NGC 1275 in 2010). The discoveries are still important for extending our knowledge on the population of the VHE γ-ray emitting AGN. The MAGIC AGN observing program has been very successful in discovering new sources and putting constrains on emission mechanism and emission site of the VHE γ-rays in known sources.

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References

[1] Klepser S and for the MAGIC Collaboration 2011 ArXiv e-prints (Preprint 1104. 0863)
[2] The HEGRA Collaboration Aharonian F and et al 2003 Astronomy & Astrophysics 403 L1–L5 (Preprint arXiv:astro-ph/0302155)
[3] The HESS Collaboration Aharonian F and et al 2009 Astrophysical Journal Letters 695 L40–L44 (Preprint 0903.1582)
[4] Mariotti M and MAGIC Collaboration 2010 The Astronomer’s Telegram 2916 1–+
[5] Neronov A, Semikoz D and Vovk I 2010 Astronomy & Astrophysics 519 L6+ (Preprint 1003.4615)
[6] The MAGIC Collaboration Aleksić J and et al 2010 Astrophysical Journal Letters 723 L207–L212 (Preprint 1009.2155)
[7] Hartman R C, Böttcher M, Aldering G and et al 2001 Astrophysical Journal 553 683–694 (Preprint arXiv:astro-ph/0102127)
[8] Dermer C D and Schlickeiser R 1993 Astrophysical Journal 416 458–4
[9] Sikora M, Begelman M C and Rees M J 1994 Astrophysical Journal 421 153–162
[10] Mannheim K and Biermann P L 1992 Astronomy & Astrophysics 253 L21–L24
[11] Mücke A, Protheroe R J, Engel R and et al 2003 Astroparticle Physics 18 593–613 (Preprint arXiv:astro-ph/0206164)
[12] Böttcher M, Reimer A and Marscher A P 2009 Astrophysical Journal 703 1168–1175
[13] Sitarek J and Bednarek W 2008 Monthly Notices of the Royal Astronomical Society 391 624–638 (Preprint 0807.4228)
