1 Introduction

One of the major goals of ground-based $\gamma$-ray astrophysics is the study of VHE $\gamma$-ray emission from active galactic nuclei (AGN). Except for the radio galaxies M87 and Centaurus A (and possibly 3C66B), and the flat-spectrum radio quasar 3C279, all the currently known VHE $\gamma$-ray emitters in the extragalactic sky are BL Lac objects. The sensitivity of the current Imaging Atmospheric Cherenkov Telescopes (IACT) has recently enabled detailed studies of these sources in the VHE $\gamma$-rays domain, providing information for advances in understanding the origin of the VHE $\gamma$-rays, as well as powerful tools for fundamental physics studies [1].

The IACT technique [2] uses the atmosphere as a calorimeter to detect the extensive air shower produced after the interaction of a VHE $\gamma$-ray. The charged particles (mainly electrons and positrons) in the air shower produce Cherenkov light that can be easily detected in the ground with photomultipliers. A Cherenkov telescope uses a large reflector area to concentrate as much as possible of these photons and focus them to a camera where an image of the atmospheric cascade is formed. By analysing this image it is possible to reconstruct the incoming direction and the energy of the $\gamma$-ray. The analysis of the images is also used to reject the much higher background of cosmic rays initiated showers.

In this paper selected results on extragalactic observations with MAGIC are presented.

2 The MAGIC telescope

MAGIC [3,4], located on the Canary Island of La Palma (2200 m a.s.l.), is currently the largest (17-m diameter) single-dish IACT. Due to its large collection area and uniquely designed camera, MAGIC has reached the lowest energy threshold (trigger threshold 50–60 GeV at small zenith
angles, new trigger for pulsar observations $\sim 25$ GeV\(^5\) for $\gamma$-ray emission among the existing terrestrial $\gamma$-ray telescopes.

MAGIC has a sensitivity of $\sim 1.6\%$ of the Crab Nebula flux in 50 observing hours. Its energy resolution is about 30\% above 100 GeV and about 25\% from 200 GeV onwards. The angular resolution is 0.1 deg. The MAGIC standard analysis chain is described, e.g., in Albert et al.\(^6\). Observations during moderate moonshine enable a substantially extended duty cycle, which is particularly important for blazar observations. Parallel optical $R$-band observations are performed by the Tuorla Blazar Monitoring Program with its KVA 35-cm telescope.

A second MAGIC telescope is being commissioned\(^7\), which is improving the sensitivity to $\sim 0.8\%$ of Crab in 50 hours.

3 The propagation and absorption of $\gamma$-rays

While travelling long distances without deviations in the fields, VHE $\gamma$-rays suffer the absorption losses due to the interaction with the low energy photons from the extragalactic background light (EBL), limiting the distance to the source that could be detected. The standard process is $\gamma_{VHE}\gamma_{EBL} \rightarrow e^+ e^-$ pair production. The corresponding cross section\(^8\) reaches its maximum, $\sigma_{\gamma\gamma}^{\text{max}} \simeq 1.70 \cdot 10^{-25}$ cm\(^2\), assuming head-on collisions, when the background photon energy is $\epsilon(E) \simeq (0.5 \text{ TeV}/E) \text{ eV}$, $E$ being the energy of the hard (incident) photon. This shows that in the energy interval explored by the IACTs, $50 \text{ GeV} < E < 100 \text{ TeV}$, the resulting opacity is dominated by the interaction with infrared/optical/ultraviolet diffuse background photons (EBL), with $0.005 \text{ eV} < \epsilon < 10 \text{ eV}$, corresponding to the wavelength range $0.125 \mu\text{m} < \lambda < 250 \mu\text{m}$.

Based on synthetic models of the evolving stellar populations in galaxies as well as on deep galaxy counts (see, for a review,\(^9\)), several estimates of the spectral energy distribution (SED) of the EBL have been proposed, leading to different values for the transparency of the universe to $50 \text{ GeV} < E < 100 \text{ TeV}$ photons\(^10\), the resulting uncertainties are large.

Because of the absorption produced by the EBL, the observed photon spectrum $\Phi_{\text{obs}}(E_0, z)$ is related to the emitted one $\Phi_{\text{em}}(E(z))$ by

$$\Phi_{\text{obs}}(E_0, z) = e^{-\tau_{\gamma}(E_0, z)} \Phi_{\text{em}}(E_0(1 + z)) ,$$

where $E_0$ is the observed energy, $z$ the source redshift and $\tau_{\gamma}(E_0, z)$ is the optical depth\(^11\).

The energy dependence of $\tau$ leads to appreciable modifications of the observed source spectrum (with respect to the spectrum at emission) even for small differences in $\tau$, due to the exponential dependence described in Eq.\(^11\). Since the optical depth (and consequently the absorption coefficient) increases with energy, the observed flux results steeper than the emitted one. The horizon (e.g. Ref.\(^12\)) for a photon of energy $E$ is defined as the distance corresponding to the redshift $z$ for which $\tau(E, z) = 1$, which gives an attenuation by a factor $1/e$ (see Fig.\(^11\)). MAGIC has the lowest energy threshold, and thus is currently the best suited telescope to look farther away.

4 Multi-Wavelength Campaigns

Coordinated simultaneous multi-wavelength observations, yielding spectral energy distributions (SED) spanning over 15 decades in energy, have been recently conducted, and turn out to be essential for a deeper understanding of blazars. MAGIC participated in a number of multiwavelength-campaigns on known northern-hemisphere blazars, which involved the X-ray instruments Suzaku and Swift, the $\gamma$-ray telescopes H.E.S.S., MAGIC and VERITAS, and other optical and radio telescopes.
Mkn 421 was detected in two campaigns during outbursts in 2006 and 2008; the coordinated effort allowed for truly simultaneous data from optical to TeV energies, and studies of correlations between the different energy bands.

The VHE emission of PG 1553+113 showed no variability during the first multi-wavelength campaign on this blazar in July 2006, it was observed simultaneously for the first time together with AGILE during 2008.

1ES 1959+650 showed VHE data among the lowest flux state observed from this object, while at the same time a relatively high optical and X-ray flux (both Swift/Suzaku) was found. The SED could be modeled assuming a one zone SSC model, using parameters similar to the ones needed for the SED measured in 2002.

Also campaigns on 1ES 1218+304 and 1H 1426+428 have been carried out, during both of which significant X-ray variability has been observed. The VHE data are being analyzed.

Further campaigns have been and will be organized in the future.

5 Strong Flaring of Messier 87 in February 2008

M 87 is the first non-blazar radio galaxy known to emit VHE γ-rays, and one of the best-studied extragalactic black-hole systems. To enable long-term studies and assess the variability timescales and the location of the VHE emission in M 87, the H.E.S.S., MAGIC and VERITAS collaborations established a regular, shared monitoring of M 87 and agreed on mutual alerts in case of a significant detection. During the MAGIC observations, a strong signal of $8\sigma$ significance was found on 2008 February 1st, triggering the other IACTs as well as Swift observations. The analysis revealed a variable (significance: $5.6\sigma$) night-to-night γ-ray flux above 350 GeV, while no variability was found in the 150–350 GeV range. The $E > 730$ GeV short-time variability of M 87 reported by has been confirmed. This fastest variability $\Delta t$ observed so far in TeV γ-rays in M 87 is on the order of or even below one day, suggesting the core of M 87 as the origin of the TeV γ-rays. M 87 is the first radio galaxy that shows evidence for a connection between simultaneously and well sampled radio and VHE flux variations, opening a new avenue for the study of AGN accretion and jet formation.
6 Blazars Detected during Optical Outbursts

MAGIC has been performing target of opportunity observations upon high optical states of known or potential VHE $\gamma$-ray emitting extragalactic sources. Up to now, this strategy has been proven very successful, with the detection of Mkn 180\textsuperscript{23}, 1ES 1011+496\textsuperscript{24}, and recently S5 0716+71\textsuperscript{25} (paper in preparation).

In April 2008, KVA observed a high optical state of the blazar S5 0716+71, triggering MAGIC observation, which resulted in a detection of a strong 6.8 $\sigma$ signal, corresponding to a flux of $F_{300\text{GeV}} \approx 10^{-11}$ cm$^{-2}$ s$^{-1}$. The MAGIC observation time was 2.6 h. The source was also in a high X-ray state\textsuperscript{26}.

The determination of the before-unknown redshifts of 1ES 10 11+496 ($z = 0.21$)\textsuperscript{24} and S5 0716+71 ($z = 0.31$)\textsuperscript{27} makes these objects the third-most and second-most distant TeV blazars after 3C 279, respectively.

7 The region of 3C66A/B

The MAGIC telescope observed the region around the distant blazar 3C 66A for 54.2 h in August–December 2007. The observations resulted in the discovery of a $\gamma$-ray source centered at celestial coordinates R.A. = 2$^h$23$^m$12$^s$ and decl. = 43$^\circ$0$^\prime$.7 (MAGIC J0223+430), coinciding with the nearby radio galaxy 3C 66B\textsuperscript{28}. The energy spectrum of MAGIC J0223+430 follows a power law with a normalization of $(1.7 \pm 0.3_{\text{stat}} \pm 0.6_{\text{syst}}) \times 10^{-11}$ TeV$^{-1}$ cm$^{-2}$ s$^{-1}$ at 300 GeV and a photon index $\Gamma = -3.10 \pm 0.31_{\text{stat}} \pm 0.2_{\text{syst}}$. A possible association of the excess with the blazar 3C 66A and nearby radiogalaxy 3C 66B is discussed in these proceedings\textsuperscript{29}.

8 Detection of the flat-spectrum radio quasar 3C 279

Observations of 3C 279, the brightest EGRET AGN\textsuperscript{30}, during the WEBT multi-wavelength campaign\textsuperscript{31} revealed a 5.77 $\sigma$ post-trial detection on 2006 February 23\textsuperscript{rd} supported by a marginal signal on the preceding night\textsuperscript{32}. The overall probability for a zero-flux lightcurve can be rejected on the 5.04 $\sigma$ level. Simultaneous optical $R$-band observations by the Tuorla Observatory Blazar Monitoring Program revealed that during the MAGIC observations the $\gamma$-ray source was in a generally high optical state, a factor of 2 above the long-term baseline flux, but with no indication of short time-scale variability at visible wavelengths. The observed VHE spectrum can be described by a power law with a differential photon spectral index of $\alpha = 4.1 \pm 0.7_{\text{stat}} \pm 0.2_{\text{syst}}$ between 75 and 500 GeV (Fig. 2). The measured integrated flux above 100 GeV on February 23\textsuperscript{rd} is $(5.15 \pm 0.82_{\text{stat}} \pm 1.5_{\text{syst}}) \times 10^{-10}$ photons cm$^{-2}$ s$^{-1}$.

This detection extends the test on the transparency of the universe up to $z = 0.536$; the $\gamma$-ray horizon together with the IACT measurements is shown in Fig. 3 from\textsuperscript{32}.

VHE observations of such distant sources were until recently impossible due to the expected strong attenuation of $\gamma$ rays by the EBL, which influences the observed spectrum and flux, resulting in an exponential decrease with energy and a cutoff in the $\gamma$-ray spectrum. The reconstructed intrinsic spectrum is difficult to reconcile with models predicting high EBL densities, while low-level models, e.g.\textsuperscript{10} are still viable. Assuming a maximum intrinsic photon index of $\alpha^* = 1.5$, an upper EBL limit is inferred, leaving a small allowed region for the EBL.

In Fig. 4 the observed values of the spectral indexes of the blazars detected so far in VHE band are shown, together with the prediction (light grey area) of the standard scenario. The recent findings suggest a higher transparency of the universe to VHE photons than expected from current models of the EBL, and could be interpreted in terms of more exotic scenarios\textsuperscript{34}. 


Figure 2: Spectrum of 3C 279 measured by MAGIC. The grey area includes the combined statistical (1σ) and systematic errors, and underlines the marginal significance of detections at high energy. The dotted line shows compatibility of the measured spectrum with a power law of photon index $\alpha = 4.1$. The blue and red triangles are measurements corrected on the basis of the two models for the EBL density.

Figure 3: The γ-ray horizon. The redshift region over which it can be constrained by observations has been extended by MAGIC up to $z=0.536$. 
The July-2005 Flares of Mkn 501

Mkn 501 \((z = 0.034)\) is known to be a strong and variable VHE \(\gamma\)-ray emitter. MAGIC observed Mkn 501 for 24 nights during six weeks in summer 2005. In two of these (one with moon present), the recorded flux exceeded four times the Crab-nebula flux, and revealed rapid flux changes with doubling times as short as 3 minutes or less. For the first time, short \((\approx 20 \text{ min})\) VHE \(\gamma\)-ray flares with a resolved time structure could be used for detailed studies of particle acceleration and cooling timescales. In addition, a time delay between different energy bins could be investigated, and gave some hints of a delay of the higher energy photons\(^{35}\).

An energy-dependent speed of photons in vacuum is expected as a generic signature in some approaches to Quantum Gravity (QG) theories, where Lorentz invariance violation is a manifestation of the foamy structure of space-time at short distances. It could be reflected in modifications of the propagation of energetic particles, i.e. dispersive effects due to a non-trivial refractive index induced by the fluctuations in the space-time foam\(^{38}\). The dependence of the speed of light on the energy \(E\) of the photon can be parameterized as

\[
c' = c \left[ 1 \pm \left( \frac{E}{E_{S1}} \right) \pm \left( \frac{E}{E_{S2}} \right)^2 \pm \ldots \right].
\]

The energy scales \(E_{S1}, E_{S2}\) are usually expressed in units of the Planck mass, \(M_P \equiv 1.22 \times 10^{19} \text{ GeV}/c^2\). If the linear term dominates, Eq. (2) reduces to

\[
c' = c \left[ 1 \pm \left( \frac{E}{E_{S1}} \right) \right].
\]

A favored way to search for such a dispersion relation is to compare the arrival times of photons of different energies arriving on Earth from pulses of distant astrophysical sources (see\(^{39}\) for a review).

The reanalysis of the Mkn 501 data in\(^{36}\) resulted in a much-improved estimate of the time-energy relation. At a zero-delay probability of \(P = 0.026\), a marginal time delay of \(\tau_l = (0.030 \pm 0.012) \text{ s GeV}^{-1}\) towards higher energies was found using two independent analyses, both exploiting the full statistical power of the dataset (see\(^{37}\) for details). Since it is not possible to exclude that this delay is due to some energy-dependent effect at the source, because the emission mechanisms are not currently understood, a lower limit of
$E_{S1} > 0.21 \times 10^{18}$ GeV (95% c.l.) can be established. However, if the emission mechanism at the source were understood and the observed delays were mainly due to propagation, this number could turn into a real measurement of $E_{S1}$.

This pioneering study demonstrates clearly the potential scientific value of an analysis of multiple flares from different sources.

10 Conclusions

After almost 4 observation cycles, MAGIC observations of the extragalactic TeV γ-ray sources contributed to many physics insights, confirming the rich potential of VHE γ-ray astrophysics. Among the currently detected 27 VHE γ-ray emitters, MAGIC has discovered 8 new sources, and detected and studied 5 known ones.

In Fig. 5, the skymap of the detected sources, together with the MAGIC field of view, is shown (see this reference also for an up-to-date list).

Important contributions to the understanding of active galactic nuclei have been given, allowing both to infer the intrinsic properties of the sources and to probe the nature of photon propagation through cosmic distances.

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