Status and recent results of MAGIC

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Abstract.
MAGIC is a single-dish Cherenkov telescope located on La Palma (Spain), hence with an optimal view on the Northern sky. Sensitive in the 30 GeV – 30 TeV energy band, it is nowadays the only ground-based instrument being able to measure high-energy γ-rays below 100 GeV. We review the most recent experimental results obtained using MAGIC.

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INTRODUCTION: THE MAGIC TELESCOPE

The Major Atmospheric Gamma Imaging Cherenkov (MAGIC) telescope is a last-generation instrument for very high energy (VHE) γ-ray observation exploiting the Imaging Air Cherenkov (IAC) technique. This kind of instrument images the Cherenkov light produced in the particle cascade initiated by a γ-ray in the atmosphere. Located on the Roque de los Muchachos Observatory, in La Palma (Spain), MAGIC incorporates a number of technological improvements in its design and achieves the lowest energy threshold (55 GeV with the nominal trigger, 25 GeV with the pulsar trigger [1]) among instruments of its kind. MAGIC signal digitization utilizes 2 GSample/s Flash Analog-to-Digital Converters, and timing parameters are used during the data analysis [2], yielding a sensitivity (at a flux peak energy of 280 GeV) of 1.6% of the Crab Nebula flux in 50 hours of observations. The relative energy resolution above 200 GeV is better than 30%. The angular resolution is ~ 0.1°, while source localization in the sky is provided with a precision of ~ 2'. MAGIC is also unique among IAC telescopes by its capability to operate under moderate illumination [3] (i.e. moon or twilight). This allows to increase the duty cycle by a factor 1.5 and a better sampling of variable sources is possible. The construction of a second telescope is now in its final stage and MAGIC will start stereoscopic observations in the following weeks.

MAGIC has been operating since fall 2004, developing a physics program which includes both, topics of fundamental physics and astrophysics. In this paper we highlight MAGIC latest contributions to Extragalactic [4, 5, 6, 7, 8, 9, 10, 11, 12] and Galactic [1, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25] astrophysics.
EXTRAGALACTIC OBSERVATIONS

Except for the radio galaxy M 87, all 23 currently known VHE γ-ray emitting AGNs [26] are high-frequency peaked BL Lac objects. Their two-bumped spectral energy distributions (SED) are characterized by a second peak at very high γ-ray energies. In synchrotron-self-Compton (SSC) models this peak is assumed to be due to the inverse-Compton (IC) of electrons, by upscattering previously produced synchrotron photons to high energies. In hadronic models, instead, interactions of a highly relativistic jet outflow with ambient matter, proton-induced cascades, or synchrotron radiation off protons, are the origin of the high-energy photons. Another defining property of blazars is the high variability of their emission ranging from radio to γ-rays. For VHE γ-ray blazars, correlations between X-ray and γ-ray emission have been found on time scales ranging from ~10 minutes to days and months (see, e.g., Fossati et al. [27]), although the correlations have proven to be rather complicated [28].

Here we present selected results from multi-wavelength (MWL) campaigns with MAGIC participation and for observations of the AGN Mkn 501, M 87 (February 2008), 1ES 1011+496, S5 0716+71, and 3C 279.

Multi-Wavelength Campaigns

For an advanced understanding of blazars, coordinated simultaneous MWL observations are essential, as they allow the determination of SEDs spanning over 15 orders of magnitude in energy. In the 2006/7 season, MAGIC participated in multiwavelength-campaigns carried out on the blazars Mkn 421, Mkn 501, PG 1553+113, 1ES 1218+304, 1H 1426+428, and the radio galaxy M 87. These campaigns involved the X-ray satellites INTEGRAL, Suzaku and Swift, the γ-ray telescope H.E.S.S., VERITAS, and MAGIC, and other optical and radio telescopes. We discuss some of the campaigns in more detail here.

The observations of Mkn 501 in July 2006 revealed the lowest X-ray and VHE state ever observed. No variability in VHE γ-rays was found, while an overall increase of about 50% during one day was seen in X-rays. A one-zone SSC model describes this quiescent state of Mkn 501 well [29]. Campaigns on 1ES 1218+304 and 1H 1426+428 have been carried out, during both of which significant X-ray variability has been observed. Mkn 421 was observed together with INTEGRAL, Suzaku and Swift and showed interesting intra-day variability during some of the observation nights. The VHE data of these observations are currently being analyzed. A more recent observation of a flare of Mkn 421 in summer 2008 could be followed accurately from optical to VHE γ rays, with the participation of AGILE, GASP-WEBT, VERITAS and MAGIC [30]. During the first multi-wavelength campaign ever on PG 1553+113 in July 2006, its VHE emission showed no variability [31]. 1ES 1959+650 showed VHE data among the lowest flux state observed from this object, while at the same time a relatively high

2 See http://www.mpp.mpg.de/~rwagner/sources/ for an up-to-date source list.
FIGURE 1. The night-by-night light curve for M 87 as measured from 2008 January 30 to 2008 February 11. Left: The flux in the energy bin 150 – 350 GeV is consistent with a constant emission. Right: Flux variations are apparent on variability timescales down to 1 day in the integral flux above 350 GeV, instead. The inset shows the light curve above 350 GeV in a 40 min time binning for the night with the highest flux (2008 February 1). The vertical arrows represent flux upper limits (95% c.l.) for the nights with negative excesses.

optical and X-ray flux (both Suzaku and Swift) was found\[7\]. The SED could be modeled using similar parameters as needed for the SED measured in 2002, with a slightly more compact source and a slightly lower magnetic field.

**Strong Flaring of Messier 87 in February 2008**

The giant radio galaxy M 87 has been known as VHE $\gamma$-ray emitter (Aharonian et al.\[32\] and refs. therein), and is also one of the best-studied extragalactic black-hole systems. To assess variability timescales and the location of the VHE engine in M 87, the H.E.S.S., VERITAS, and MAGIC collaborations carried out a shared monitoring of M 87, resulting in $\approx$ 120 h observations in 2008\[33\]. Results from the entire campaign will appear in a dedicated paper. During the MAGIC observations, a strong 8 $\sigma$ signal was found on 2008 February 1, triggering the other Cherenkov telescopes as well as Swift observations. For the first time, MAGIC determined the energy spectrum below 250 GeV\[4\], which can be described by a power law with a spectral index of $\Gamma = 2.30 \pm 0.11_{\text{stat}} \pm 0.20_{\text{syst}}$. We did not measure a high-energy cutoff, but found a marginal spectral hardening, which may be interpreted as a similarity to other blazars detected at VHE, where such hardening has often been observed\[26\]. Our analysis revealed a variable (5.6 $\sigma$) night-to-night $\gamma$-ray flux above 350 GeV, while no variability was found for 150–350 GeV (Fig. 1). This fastest variability $\Delta t$ observed so far in TeV $\gamma$-rays in M 87, confirming the $E > 730$ GeV short-time variability reported earlier\[32\], is on the order of or even below one day, restricting the emission region to a size of $R \leq \Delta t c \delta = 2.6 \times 10^{15}$ cm $= 2.6 \delta$ Schwarzschild radii (Doppler factor $\delta$), and suggests the core of M 87 rather than the brightest known knot in the M 87 jet, HST-1, as the origin of the TeV $\gamma$-rays. During the MAGIC observations HST-1 was at a historically low X-ray flux level, whereas at the same time the core luminosity reached a historical maximum (D. Harris, priv. comm.). This strongly supports the core as the VHE $\gamma$-ray emission region.
The July-2005 Flares of Mkn 501

MAGIC observed the bright and variable VHE γ-ray emitter Mkn 501 during six weeks in summer 2005 [5]. In two of the observation nights, the recorded flux (> 4 × that of the Crab nebula) revealed rapid changes with doubling times as short as 3 minutes or less. For the first time, short (≈ 20 min) VHE γ-ray flares with a resolved time structure could be used for detailed studies of particle acceleration and cooling timescales.

Interestingly the flares in the two nights behave differently: While the 2005 June 30 flare is only visible in 250 GeV–1.2 TeV, the 2005 July 9 flare is apparent in all energy bands (120 GeV to > 1.2 TeV). Additionally, a photon-by-photon analysis of the July 9 flare [6] revealed a time delay between the flare peak at different energies: At a zero-delay probability of \( P = 0.026 \), a marginal time delay of \( \tau_l = (0.030 \pm 0.012) \) s GeV\(^{-1}\) towards higher energies was found using two independent analyses, both exploiting the full statistical power of the dataset. Several explanations for this delay have been considered up to now: (1) Particles inside the emission region moving with constant Doppler factor need some time to be accelerated to energies that enable them to produce the highest energy γ rays [5]. (2) The γ-ray emission has been captured in the initial acceleration phase of the relativistic blob in the jet, which at any point in time radiates up to highest γ-ray energies possible [34]. (3) A one-zone SSC model, which invokes a brief episode of increased particle injection at low energies [35]. (4) An energy-dependent speed of photons in vacuum [36], as predicted in some models of quantum gravity [37]. When assuming a simultaneous emission of the γ-rays (of different energies) at the source, a lower limit of \( M_{\text{QG}} > 0.21 \times 10^{18} \) GeV (95% c.l.) can be established [6].

Blazars Detected during Optical Outbursts

MAGIC has been performing target of opportunity observations upon high optical states of known or potential VHE blazars. Up to now, this strategy has proven very successful with the discovery of Mkn 180 [8], 1ES 1011+496 [9], and recently S5 0716+71 [11]. The 18.7-h observation of 1ES 1011+496 was triggered by an optical outburst in March 2007, resulting in a 6.2 \( \sigma \) detection at \( F_{>200\text{GeV}} = (1.58 \pm 0.32) \times 10^{-11} \text{cm}^{-2} \text{s}^{-1} \) [9]. An indication for an optical–VHE correlation is given, in that in spring 2007 the VHE γ-ray flux is >40% higher than in spring 2006, where MAGIC observed the blazar as part of a systematic search for VHE emission from a sample of X-ray bright (\( F_{1\text{keV}} > 2 \mu\text{Jy} \)) HBLs [10]. In April 2008, a high optical state of the blazar S5 0716+71, triggered MAGIC observations, which resulted in the detection of a strong 6.8 \( \sigma \) signal in 2.6 h, corresponding to a flux of \( F_{>400\text{GeV}} \approx 10^{-11} \text{cm}^{-2} \text{s}^{-1} \) [11]. The source was also in a high X-ray state [38]. The determination of the before-unknown redshifts of 1ES 1011+496 (\( z = 0.21 \), [9]) and S5 0716+71 (\( z = 0.31 \), [39]) makes these objects the third-most and second-most distant TeV blazars after 3C 279, respectively.
Detection of the flat-spectrum radio quasar 3C 279

Observations of 3C 279, the brightest EGRET AGN [40], revealed a 5.77 $\sigma$ post-trial detection on 2006 February 23 supported by a marginal signal on the preceding night [12]. The overall probability for a zero-flux lightcurve can be rejected on the 5.04 $\sigma$ level. Simultaneous optical $R$-band observations found 3C 279 in a high optical state, a factor of 2 above its long-term baseline flux, but with no indication of short time-scale variability. 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 23 February is $(5.15 \pm 0.82_{\text{stat}} \pm 1.5_{\text{syst}}) \times 10^{-10}$ photons cm$^{-2}$ s$^{-1}$.

VHE observations of sources as distant as 3C 279 ($z = 0.536$) were until recently deemed impossible due to the expected strong attenuation of the $\gamma$-ray flux by the extragalactic background light (EBL), resulting in an exponential decrease with energy and a cutoff in the $\gamma$-ray spectrum. The observed VHE spectrum is sensitive to the EBL between 0.2 – 2$\mu$m. The reconstructed intrinsic spectrum of 3C 279 is difficult to reconcile with models predicting high EBL densities (e.g., the fast-evolution model of Stecker et al. [41]), while low-level models, e.g. [42, 43], 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.

The results support, at higher redshift, the conclusion drawn from earlier measurements [43] that the observations of the Hubble Space Telescope and Spitzer correctly estimate most of the light sources in the Universe.
In this section we review our latest results on Galactic astrophysics.

The unidentified \(\gamma\)-ray source TeV 2032+4130

The TeV source J2032+4130 was the first unidentified VHE \(\gamma\)-ray source, and also the first discovered extended TeV source, likely to be Galactic [44]. The field of view of TeV J2032+4130 was observed with MAGIC for 93.7 hours of good-quality data, between 2005 and 2007 [13]. The source is extended with respect to the MAGIC PSF (see Figure 3). Its intrinsic size assuming a Gaussian profile is \(\sigma_{\text{src}} = 5.0 \pm 1.7_{\text{stat}} \pm 0.6_{\text{sys}}\) arcmin. The energy spectrum is well fitted \((\chi^2/n.d.f = 0.3)\) by the following power law:

\[
\frac{dN}{dE \, dAdt} = (4.5 \pm 0.3) \times 10^{-13} (E / 1 \text{ TeV})^{-2.0 \pm 0.3} \text{ TeV}^{-1} \text{cm}^{-2} \text{s}^{-1}.
\]

Quoted errors are statistical, the systematic error is estimated to be 35% in the flux level and 0.2 in the photon index [19]. The MAGIC energy spectrum (see Figure 3) is compatible both in flux level and photon index with the one measured by HEGRA, and extends it down to 400 GeV. We do not find any spectral break, nor any flux variability over the 3 years of MAGIC observations.

Shell-type Supernova Remnants: Cassiopeia A and IC 433

We observed the shell-type supernova remnant (SNR) Cassiopeia A during 47 good-quality hours, and detected a point-like source of VHE \(\gamma\)-rays above \(\sim 250\) GeV [14]. The measured spectrum is consistent with a power law with a differential flux at 1 TeV of \((1.0 \pm 0.1_{\text{stat}} \pm 0.3_{\text{sys}}) \times 10^{-12} \text{ TeV}^{-1} \text{cm}^{-2} \text{s}^{-1}\) and a photon index of...
FIGURE 4. Left: Spectrum of Cas A as measured by MAGIC. The upper limits given by Whipple, EGRET and CAT are also indicated, as well as the HEGRA detection. The MAGIC and HEGRA spectra are shown in the context of the model by [46]. Right: Sky map of $\gamma$-ray candidate events (background subtracted) in the direction of MAGIC J0616+225 for an energy threshold of about 150 GeV. Overlayed are $^{12}$CO emission contours, contours of 20 cm VLA radio data, X-ray contours and $\gamma$-ray contours from EGRET. The white star denotes the position of the pulsar CXOU J061705.3+222127. The black dot shows the position of the 1720 MHz OH maser.

$\Gamma=2.4\pm0.2_{\text{stat}}\pm0.2_{\text{sys}}$. The spectrum measured about 8 years later by MAGIC is consistent with that measured by HEGRA [45] for the energies above 1 TeV, i.e. where they overlap (see Figure 4 Left). Our results seem to favor a hadronic scenario for the $\gamma$-ray production, since a leptonic origin of the TeV emission would require low magnetic field intensities, which is in principle difficult to reconcile with the high values required to explain the rest of the broad-band spectrum. However, hadronic models [46] predict for the 100 GeV – 1 TeV region a harder spectrum than then measured one.

We have detected a new source of VHE $\gamma$-rays located close to the Galactic Plane, namely MAGIC J0616+225 [15], which is spatially coincident with the SNR IC 443. The measured energy spectrum is well fitted ($\chi^2/n.d.f = 1.1$) by the following power law: $dN/dE/d\Omega d\tau = (1.0 \pm 0.2) \times 10^{-11} (E/0.4\text{ TeV})^{-3.1\pm0.3}\text{ TeV}^{-1}\text{cm}^{-2}\text{s}^{-1}\text{ sr}^{-1}$. MAGIC J0616+225 is point-like for MAGIC spatial resolution, and appears displaced to the south of the center of the SNR shell, and correlated with a molecular cloud [47] and the location of maser emission [48] (see Figure 4 Right). There is also an EGRET source centered in the shell of the supernova remnant. The observed VHE radiation may be due to $\pi^0$-decays from interactions between cosmic rays accelerated in IC 443 and the dense molecular cloud. A possible distance of this cloud from IC 443 could explain the steepness of the measured VHE $\gamma$-ray spectrum.

Wolf-Rayet binaries

WR stars display some of the strongest sustained winds among galactic objects with terminal velocities reaching up to $v_\infty > 1000 − 5000\text{ km/s}$ and also one of the highest known mass loss rate $\dot{M} \sim 10^{-4} − 10^{-5}\text{ }M_\odot/\text{yr}$. Colliding winds of binary systems containing a WR star are considered as potential sites of non-thermal high-energy photon
production, via leptonic and/or hadronic process after acceleration of primary particles in the collision shock (see, e.g., [49]).

We have selected two objects of this kind, namely WR 147 and WR 146, and observed them for 30.3 and 44.5 effective hours, respectively [16]. No evidence for VHE γ-ray emission has been detected in either case, and upper limits to the emission of 1.5, 1.4 and 1.7% (WR 147) and 5.0, 3.5 and 1.2% (WR 146) of the Crab Nebula flux are derived for lower energy cuts of 80, 200 and 600 GeV, respectively. These limits are shown in Figure 5 (Left) for the case of WR 147, compared with a theoretical model [49].

Compact binaries: Cygnus X-1 and LS I +61 303

Cygnus X-1 is the best established candidate for a stellar mass black-hole (BH) and one of the brightest X-ray sources in the sky. We have observed it for 40 hours along 26 different nights between June and November 2006. Our observations have imposed the first limits to the steady γ-ray emission from this object, at the level of 1% of the Crab Nebula flux above \(\sim 500\) GeV. We have also obtained a very strong evidence (4.1 \(\sigma\) post-trial significance) of a short-lived, intense flaring episode during 24th September 2006, in coincidence with a historically high flux observed in X-rays [50] and during the maximum of the \(\sim 326\)d super-orbital modulation [51]. The detected signal is point-like, consistent with the position of Cygnus X-1. The nearby radio-nebula produced by the jet interaction with the interstellar medium [52] is excluded as the possible origin of an eventual putative emission (see Figure 5 Right).

LS I +61 303 is a very peculiar binary system containing a main-sequence star together with a compact object (neutron star or black hole), which displays periodic emission throughout the spectrum from radio to X-ray wavelengths. Observations with MAGIC have determined that this object produces γ-rays up to at least \(\sim 4\) TeV [18], and that the emission is periodically modulated by the orbital motion \((P_{\text{TeV}} = (26.8 \pm 0.2) \text{ d}) [24]\) (see Figure 6 Left). The peak of the emission is found always at orbital phases around
0.6–0.7. During December 2006 we detected a secondary peak at phase 0.8–0.9. Between October-November 2006, we set up a multiwavelength campaign involving radio (VLBA, e-EVN, MERLIN), X-ray (Chandra) and TeV (MAGIC) observations [25]. We have excluded the existence of large scale (∼100 mas) persistent radio-jets, found a possible hint of temporal correlation between the X-ray and TeV emissions and evidence for radio/TeV non-correlation.

Crab Nebula and Pulsar

The Crab Nebula is the standard candle for VHE astrophysics and as such, a big fraction of MAGIC observation time is devoted to this object. Out of it, we have used 16 hours of optimal data to measure the energy spectrum between 60 GeV and 8 TeV [19]. The peak of the SED has been measured at an energy $E = (77 \pm 35)$ GeV. The VHE source is point-like and the position coincides with that of the pulsar. More recently, thanks to a special trigger setup, we have detected pulsed emission coming from the Crab pulsar above 25 GeV (see Figure 6 Right), with a statistical significance of $6.4 \sigma$ [1]. This result has revealed a relatively high energy cutoff, indicating that the emission occurs far out in the magnetosphere, hence excluding the polar-cap scenario as a plausible explanation for the high-energy origin. This is also the first time that a pulsed γ-ray emission is detected from a ground-based telescope, and opens the possibility of a detailed study of the pulsar’s energy cutoff, which will help elucidate the mechanism of high energy radiation in these objects. More details can be found at [53].

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