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Review

Highlights of the Magic Florian Goebel Telescopes in the Study of Active Galactic Nuclei

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Abstract: The MAGIC (Major Atmospheric Gamma-ray Imaging Cherenkov) Florian Goebel telescopes are a system of two Cherenkov telescopes located on the Canary island of La Palma (Spain), at the Roque de Los Muchachos Observatory, which have been operating in stereo mode since 2009. Their low energy threshold (down to 15 GeV) allows the investigation of Active Galactic Nuclei (AGNs) in the very-high-energy (VHE, E > 100 GeV) gamma-ray range with a sensitivity up to the redshift limit of the existing IACT (Imaging Atmospheric Cherenkov Telescopes) systems. The MAGIC telescopes discovered 36 extragalactic objects emitting VHE gamma-rays and performed comprehensive studies of galaxies and their AGNs, also in a multi-wavelength (MWL) and multi-messenger (MM) context, expanding the knowledge of our Universe. Here, we report on the highlights achieved by the MAGIC collaboration since the beginning of their operations.

Keywords: γ-ray astrophysics; active galactic nuclei; very-high-energy gamma rays; non-thermal; high energy astrophysics

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1. Introduction

The main targets of high-energy extragalactic astrophysics are Active Galactic Nuclei (AGNs), galaxies powered by a central supermassive black hole ($M_\bullet \gtrsim 10^6\ M_\odot$, where $M_\bullet$ is the mass of the black hole and $M_\odot \approx 2 \times 10^{30}$ Kg is the solar mass) emitting non-thermal photons across the electromagnetic spectrum. AGNs whose radiation reaches the gamma-ray energy range account for only 10% of the AGNs observed in our Universe, and they exhibit collimated jets of relativistic plasma. The presence of the jet is closely linked to gamma-ray emission, and when such a jet is oriented in the direction of the observer, AGNs are called blazars and are further subdivided into BL Lac-type objects (BL Lacs) and Flat Spectrum Radio Quasars (FSRQs). AGNs can show variability in all energy bands, and due to the many studies and observations that have been conducted in each band, categorizing such objects can be challenging. When AGNs emit from the radio to the VHE (very-high-energy, E > 100 GeV) gamma-ray band, they present a double-peaked spectral energy distribution (SED) (e.g., [1]) that can be studied to identify and predict the emission mechanism of the radiation. The first bump, which extends between radio and X-ray energies, is universally attributed to synchrotron radiation emanating from a population of electrons rotating in the magnetic field of the AGN, while the second bump, which can reach VHE gamma-ray energies, can be explained, depending on the position and on its shape, by different theoretical models which can be fully leptonic or including an hadronic component. In the synchrotron self-Compton model (SSC, [2,3]), the high-energy bump is attributed to the inverse Compton scattering of lower-energy photons by relativistic electrons and is therefore often referred to as the IC bump. The SSC model is a leptonic model that successfully describes the MWL SED of most blazars, but in some cases it is necessary to consider an external component responsible for the emission of high-energy (HE, 100 MeV < E < 100 GeV) or VHE gamma rays, as in leptonic EC (external Compton) models (i.e., [4]). In the case of FSRQs, for example, the external radiation fields can be the accretion disk, broad-line region (BLR) or a dusty torus. In hadronic models, the high-energy gamma rays can also be produced by relativistic protons, by proton-synchrotron radiation or by photopion production. For more details on the theoretical models, see for example a review of the theoretical challenges in the study of AGNs [5,6] for a review of the results of high energy gamma-ray observations in the context of radiative mechanisms and models.

The subdivision of blazars into the subclasses BL Lacs and FSRQs is based on the absence or presence of emission/absorption lines in their optical spectra. BL Lacs have faint lines while the optical spectra of FSRQs have strong resolved lines that suggest the presence of radiatively efficient accretion disks and that can be measured providing a value for the luminosity and consequently the mass of their black-hole [7]. BL Lacs can be further categorized according to the position of the peak of their synchrotron bump, which can be measured by their broadband SED. They are defined as LBL (low-energy peaked), HBL (high-energy peaked) or IBL (intermediate) if their synchrotron peaks are in the submillimeter to infrared energy bands, in the ultraviolet to X-ray energy bands, or in the middle between the two aforementioned cases, respectively.

An effective recent categorization consists of dividing AGNs into two main classes, jetted and non-jetted AGNs [8]. This approach is very effective as it decouples the study of AGNs from features attributed to a single energy band and projects them in a multi-wavelength (MWL) and multi-messenger (MM) context. It is therefore of utmost importance to collect simultaneous data in a MWL context and investigate the time scale of the variability at different energies, correlations between the energy bands, polarization and periodicities, in order to derive a theoretical interpretation of the dataset and shed light on the emission scenarios of AGNs. In this context, the most important goals are:

- to determine the location of the gamma-ray and VHE gamma-ray emission region in blazars;
- to understand the composition of blazar jets and the particle population responsible for the observed high-energy emission;
- to study the temporal evolution of MWL SEDs;
- the search for a comprehensive explanation for the correlations and anti-correlations observed between different wavebands;
- the investigation of the causes of variability.

The observation of AGNs has always been one of the priorities in the physics programme of the MAGIC Florian Goebel telescopes (Figure 1).

Figure 1. The MAGIC Florian Goebel telescopes at the Roque de Los Muchachos Observatory, Spain. Image credit: Chiara Righi.

An overview of the latest highlights of the MAGIC Florian Goebel telescopes, which concern not only AGNs but also other targets of interest in this field (such as binary star systems, gamma-ray bursts and pulsars), can be found in [9].

In this work, Section 2 is devoted to MAGIC observations of AGNs, first presenting the peculiarities and characteristics of the MAGIC system (see Section 2.1) and then the observational strategies used (see Section 2.2). Section 3 collects the results highlights obtained with the MAGIC telescopes concerning the study of AGNs and Section 4 gives a brief overview of the results of other IACTs (Imaging Atmospheric Cherenkov Telescopes). In Section 5 we summarise the results presented.

2. AGNs Studies with MAGIC

2.1. MAGIC Characteristics

The MAGIC collaboration began its activities and data taking with a single telescope, now called MAGIC I, which has been in operation at the Roque de Los Muchachos Observatory on the Canary Island of La Palma since 2004. Since 2009, a second telescope, MAGIC II, has been part of the system and the two telescopes operate simultaneously (stereo mode). MAGIC telescopes are IACTs, ground-based instruments that detect VHE gamma rays thanks to the extensive air showers they generate in the atmosphere. The Cherenkov light emitted by the charged particles in the extensive air showers is captured by the segmented mirror dishes of the IACTs and imaged by their cameras. The IACT technique is described in detail in [10–12]. The MAGIC Florian Goebel telescopes were built with the aim of lowering the energy threshold for the detection of VHE gamma rays, in order to explore more distant sources in this energy range and thus study earlier parts of the Universe. At the time MAGIC I was built, the existing IACTs operated with an energy threshold $\geq$ 300 GeV [13,14]. A lower energy threshold was also necessary to close the gap to the HE gamma-ray detectors, as the latter reach an energy of a few tenths of a GeV. The connection to HE gamma-ray data constrains the HE bump of broadband SEDs and helps to effectively determine the emission scenarios of jetted AGNs. This goal has been successfully achieved, making MAGIC the IACT system with a lower energy threshold, 50 GeV, but capable of going down to 15 GeV using a dedicated stereoscopic analog trigger (SumTriggerII, see [15]), as was the case in MAGIC's recent work on Geminga observations [16]. Important innovations were introduced in the design and construction of the telescopes compared to the other IACTs. Techniques known in accelerator particle physics experiments were used, such as fast electronics and automatic control of the instruments, as well as computers and networks capable of recording and reconstructing large volumes of data and performing interrelations. The main characteristics of MAGIC telescopes (see for details [17]) are as follows:

- Active mirror surface of 236 m^2, made of square elements 49.5 $\times$ 49.5 cm or 99 $\times$ 99 cm; f/D (focal length to diameter ratio) = 1.03;
- Support frame made of reinforced carbon fibre tubes (<70 tons);
- Approximately hexagonal camera with a diameter of 1.05 m, with 1039 PMTs of 1 inch diameter each (some PMTs of 2 inches diameter in the MAGIC I camera, see [17] for details); all PMTs have an effective quantum efficiency of 25 to 35%, depending on the wavelength; The camera is kept as light as possible and is held by an aluminium support arch, stiffened by a net of thin steel cables;
- The maximum repositioning speed is more than 7 degrees per second, which means that the telescopes can be pointed to any point on the observable sky in less than 25 s;
- Analogue signals are transmitted from the camera to the counting house via optical fibres; only the amplifiers and laser diode modulators for the transmission are located in the camera housing;
- Digitization is performed by the Domino Ring Sampler (DRS4) chip with a sampling frequency of 1.64 GHz to use the timing information in the pulse.

The performance of the MAGIC Florian Goebel telescopes is described in detail in [17,18].

2.2. Observational Strategies

Sophisticated observation strategies are used to make the observation time of the MAGIC telescopes efficient. The aim is to maximise the observing time assigned to the various scientific projects within the collaboration and to fully exploit the potential of the telescopes. The MAGIC observational cycles have a duration of one year and the allocation of observing time is based on the submission of observational proposals, which can also be carried out by external scientists (https://magic.mpp.mpg.de/public/magicop/, accessed on 12 January 2024). As far as the observation of AGNs is concerned, MAGIC strategies can be summarised in two types of approaches:

- ToO (Target of Opportunity) observations;
- monitoring with short or long cadence.

MAGIC has a long history of ToO observations that began with the start of operations [19]. ToOs are quickly organised to respond to alerts reporting increased flux from other instruments, for example from optical or HE gamma-ray telescopes. Collaboration with other instruments and facilities is key to the prompt issuance of ToO observations and the resulting rapid re-planning of targets. The collection of MWL simultaneous data allows the target sources to be investigated in a broadband context, and in the case of a non-detection, the upper limits obtained by MAGIC can still help to describe the HE part of the broadband SED and facilitate the theoretical interpretation. Most of MAGIC's detections in the VHE gamma-ray range, listed in Table 1, were made within the ToO MAGIC programme. Especially in the case of rapid variability, the timely response to alerts and the rapid rescheduling play a fundamental role.

The monitoring of specific targets has also yielded several results, as indicated in Section 3.8. The cadence of observation may vary depending on the characteristics of the target. Some AGNs are bright enough in the VHE gamma-ray range to be detected even when in a quiescent or low state, such as Mrk 421 and Mrk 501, allowing long-term monitoring with regularly repeated quick snapshots of observations, others are faint in the VHE gamma-ray range and require longer time windows for each scheduled observation. In any case, MWL campaigns are foreseen and organised in collaboration with other telescopes and facilities to obtain simultaneous data.

The observational proposals also consider observations at high zenith [20,21] and observations under moon conditions [22] for specific targets.

To reduce systematic uncertainties arising from atmospheric conditions, the MAGIC collaboration operates an elastic LIDAR (LIght Detection And Ranging) system [23]. This enables data corrections based on atmospheric transmission profiles [24].

3. Results

3.1. MAGIC Discoveries in the VHE Gamma-Ray Range

Since the beginning of operations, MAGIC has detected many AGNs emitting in the VHE gamma-ray range, 26 BL Lacs, six FSRQs (see Section 3.3), one radio galaxy (see Section 3.6) and three blazars (no final classification yet). Table 1 lists the AGNs discovered by MAGIC in the VHE gamma-ray range, ordered by their redshift.

Table 1. List of AGNs which were discovered to emit VHE gamma rays by the MAGIC telescopes. Data retrieved from TeVCat [1].

Name	Type	Redshift	Date of Announcement	References
RGB J2042+244	HBL	0.104	2019.11	[25]
Mrk 180	HBL	0.045	2006.09	[26]
TXS 0210+515	HBL	0.049	2019.01	[25]
1ES 2037+521	HBL	0.053	2016.10	[25]
1ES 1727+502	HBL	0.055	2011.11	[27]
2WHSP J073326.7+515354	HBL	0.065	2018.04	[28]

Table 1. *Cont.*

Name	Type	Redshift	Date of Announcement	References
1ES 1741+196	HBL	0.084	2011.08	[29]
B2 1811+31	IBL	0.117	2020.10	[30]
B3 2247+381	HBL	0.1187	2010.10	[31]
TXS 1515-273	HBL	0.1284	2019.02	[32]
1ES 1215+303	HBL	0.131	2011.01	[33]
RX J1136.5+6737	HBL	0.1342	2014.04	[34]
1RXS J081201.8+023735	HBL	0.1721	2021.02	([35] (video))
MAGIC J2001+435	IBL	0.1739	2010.07	[36]
1ES 1218+304	HBL	0.182	2006.05	[37]
IC 310	AGN (radio galaxy)	0.0189	2010.03	[38]
RBS 0723	HBL	0.198	2014.01	[25]
1ES 1011+496	HBL	0.212	2007.09	[39–42]
MS 1221.8+2452	HBL	0.218	2013.05	[43]
RGB J0136+391	HBL	>0.27	2012.07	[44]
H 1722+119	HBL		2013.05	[45]
1ES 0647+250	HBL	>0.29	2010.07	[46]
PKS 1413+135	Blazar	$0.247 < z < 0.5$ [47]	2022.01	[48]
S5 0716+714	IBL	0.26 [49]	2008.04	[50,51]
OT 081	LBL	0.322	2016.07	[52]
TXS 0506+056	Blazar	0.3365	2017.10	[53,54]
S2 0109+22	IBL	0.36	2015.07	[55]
S4 0954+65	Blazar	0.3694	2015.02	[56]
PKS 1222+216	FSRQ	0.432	2010.06	[57]
1ES 0033+595	HBL	0.467	2011.10	[58]
GB6 J1058+2817	BL Lac (class unclear)	0.4793 [59]	2021.04	[60]
3C 279	FSRQ	0.5362	2008.06	[61–63]
B2 1420+32	FSRQ	0.682	2020.01	[64]
TON 0599	FSRQ	0.7247	2017.12	[65]
PKS 1441+25	FSRQ	0.939	2015.04	[66]
QSO B0218+357	FSRQ	0.954	2014.07	[67,68]

[1] The TeVCat online source catalog, http://tevcat.uchicago.edu; (accessed on 12 January 2024).

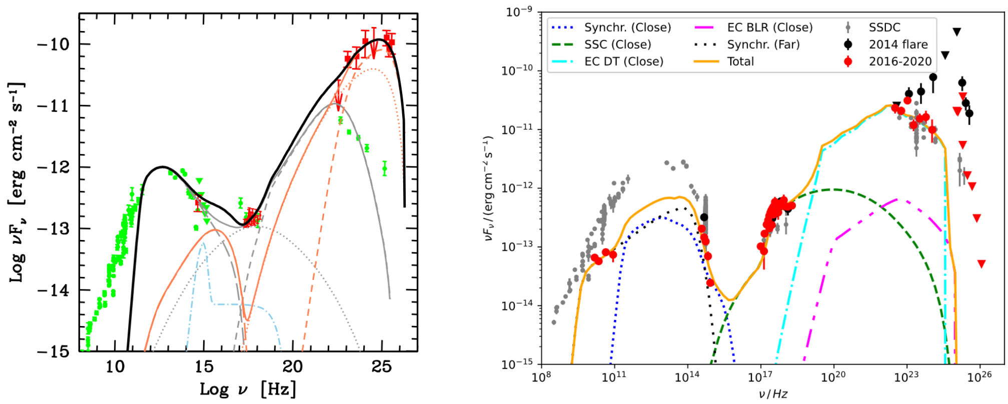
3.2. Sources at High Redshift and EBL Studies

VHE gamma rays can interact with EBL photons by pair production. This process leads to an attenuation of the flux of VHE photons, which becomes more significant with increasing distance. For this reason, IACTs have a limit to the redshift they can achieve. This depends on the EBL properties and the energy of the VHE gamma rays emitted by the source under investigation. This limit is represented by the so-called gamma-ray horizon, which is described in detail in [69,70]. Theoretical predictions made in [69] clearly show the importance of a low energy threshold for IACTs to reach sources that are as far away as possible considering EBL attenuation. Given these predictions and the measurements of the EBL made with UV and the mid-infrared telescopes [71], the detection of AGNs near redshift 1 was considered extremely difficult. Nevertheless, thanks to their particularly low energy threshold, the MAGIC telescopes succeeded in detecting to AGNs close to redshift 1 in the VHE gamma-ray range, thus pushing the limits of the gamma-ray horizon. These two discoveries were particularly important for the study of EBL with IACTs. Both sources were detected in 2014 and were both FSRQs. Only recently an even more distant FSRQ, OP 313 with a redshift of 0.99, was detected by LST-1 (Large-Sized Telescope [72,73]).

3.2.1. QSO B0218+357

QSO B0218+357, with a redshift of $z = 0.94$, was also the first gravitationally lensed blazar detected in the VHE gamma ray range, triggered by increased activity in the HE gamma-ray range. Its discovery by MAGIC occurred during the arrival time of the delayed component of the emission [67].

The MWL SED challenged a simple leptonic model and a two-zone leptonic model with an external component (emission region located inside or outside the broad line region) was used to interpret the broadband emission. This model is described in [74] (third scenario). After this peculiar detection, a MWL campaign was organized to collect more information about the emission scenario, even if during a quiescent state. Also in this case, a model with an external Compton component and two zones was necessary to interpret the data [68]. It is interesting to note the different MWL SEDs observed in the first detection case (Figure 2a) and in the quiescent state monitoring (Figure 2b).



(**a**) (**b**)

Figure 2. (**a**) Broadband SED of QSO B0218+357 during the 2014 flare. Green markers show historical data while the black solid line represents the assumed two-zone model. The red markers represent the MWL dataset. Reprinted with permission from [67]. (**b**) MWL SED of QSO B0218+357 during the monitoring campaign (red markers) compared to the 2014 flare (black markers). Reprinted with permission from [68] (Figure 11).

3.2.2. PKS 1441+25

PKS 1441+25 is a FSRQ with a redshift of z = 0.94 and was detected by MAGIC during a flaring state, triggered by high activity in the HE gamma-ray range. Its MWL SED could also not be interpreted by a simple leptonic model and an external Compton was considered, with the location of the emitting region explained as originating from the jet outside the broad line region [66]. With these distant sources, it was possible to study and measure the EBL for the first time at such a high redshift with VHE gamma-ray data, constraining the EBL density between 0.21 and 1.13 µm, as reported in [75].

3.3. Flat Spectrum Radio Quasars

FSRQs are highly luminous blazars that show strong emission lines in their optical spectra. This feature indicates the presence of a radiatively efficient accretion disk [6]. The first classification of blazars based on their gamma-ray emission, where one of the properties of FSRQs is their soft gamma index ($\Gamma > 2$), is the famous blazar sequence concept presented in [76]. Subsequent discoveries in the VHE gamma-ray range provided more material to investigate the classification of blazars and consolidate aspects of the blazar sequence while critically reconsidering and extending some of the initial considerations. A full overview on these topics can be found in [77]. Only 10 FSRQs have been confidently detected in the VHE gamma-ray range, six of which were discovered by MAGIC. MAGIC detected in 2006 the absolute first FSRQs in VHE energy, 3C 279, at a redshift of z = 0.53 [61,62]. This result was of utmost importance as it demonstrated the ability of IACTs to reach regions of the Universe where EBL attenuation is not negligible. Moreover, the emission of FSRQs in the VHE gamma-ray range leads to an MWL SED that exhibits a high Compton Dominance (CD, ratio between the so-called IC peak and the synchrotron peak). This latter property leads to a more sophisticated modelling approach with respect to BL Lacs. The high CD observed in the FSRQs detected in VHE gamma rays, was explored for the first time in detail with 3C 279. As shown in Figure 3, the MWL SED exhibits a high CD and models with an external component were required to describe the data set [62].

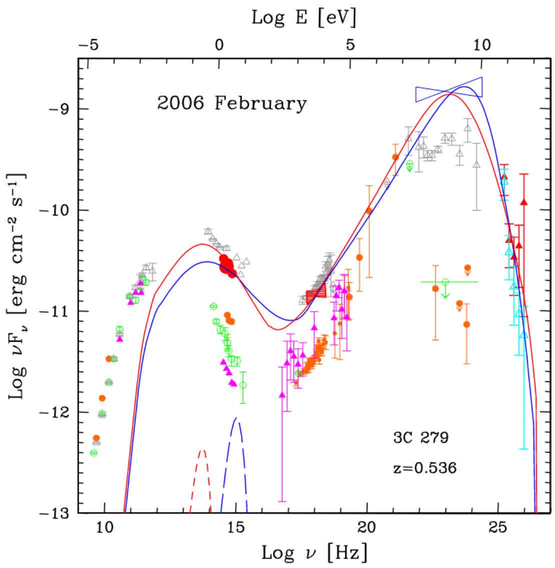


Figure 3. MWL SED of 3C 279 in 23 February 2006. The blue solid line represents the modelling under the assumption of that the external component is inside the BLR, and the red solid line when the external component is outside the BLR. Reprinted with permission from [62], Figure 8.

The second FSRQ detected by MAGIC was PKS 1222+216 in 2010 [57], and the VHE gamma-ray emission was found to be variable on a timescale of 10 min. This was an important result that made it possible to constrain the size of the gamma-ray emission region and to strongly constrain the emission models of blazar jets. The detection of PKS 1222+216 by MAGIC in fact challenged the models of jet emission and opened the discussion between different possible scenarios (far dissipation [78]; recollimation [79]; small compact emission regions in the jet [80]; reconfinement shocks [81]; relativistic filamentation [82]). The most distant FSRQs detected by MAGIC, already mentioned in Section 3.2, were detected in 2014 (QSO B0218+357) and 2015 (PKS 1441+25). After them, MAGIC detected another FSRQ in 2017, TON 0599, which lies at a redshift 0.72 [65]. This source also shows a MWL SED of complex interpretation which is the subject of a paper in preparation for the MAGIC collaboration. In 2020, MAGIC detected a new FSRQ, B2 1420+32 [64], adding another piece of the puzzle to the interpretation of such rare and powerful sources in the VHE gamma-ray sky.

3.4. Transitional Blazars

In some cases the usual categorization of blazars based on the properties of their optical spectra is complicated. BL Lacs are supposed to present an optical spectrum with very weak or absent emission lines. Instead in some cases (even for BL Lacertae), the optical spectra measured in different activity states can vary, making the categorization uncertain. Some blazars can be detected in the VHE gamma-ray range even when they are in quiescent state, while others can only be detected during flaring states of activity. Thus, it happens that some sources categorized as BL Lacs based on their optical spectra, suddenly show strong VHE gamma-ray emission in a flaring state that cannot be explained by the simplest leptonic models, which are often precise enough to describe the MWL emission of BL Lacs. Another categorization is related to the position of the synchrotron peak, which can also vary depending on the activity of the source. These sources could be called transitional sources [83], although it is not clear whether their behavior is simply related to exceptional gamma-ray activity in or to a real change in properties over time. To better understand these transitional AGNs, it is important to obtain a long-term dataset in

MWL. MAGIC observed and detected for the first time in the VHE gamma-ray range two AGNs categorized as BL Lacs, but from the MWL dataset collected simultaneously with the MAGIC observations, they were found to have properties close to those of FSRQs. The first, S4 0954+65, was observed by MAGIC in 2015 and studied in an MWL context in [56]. It was found that the MWL SED of S4 0954+65 is reproduced by a leptonic model typical of FSRQs with an external Compton component (dusty torus). Similarly, the blazar OT 081, observed and detected in 2016 by MAGIC together with H.E.S.S. shows features of FSRQs rather than BL Lacs, in particular the high CD [52].

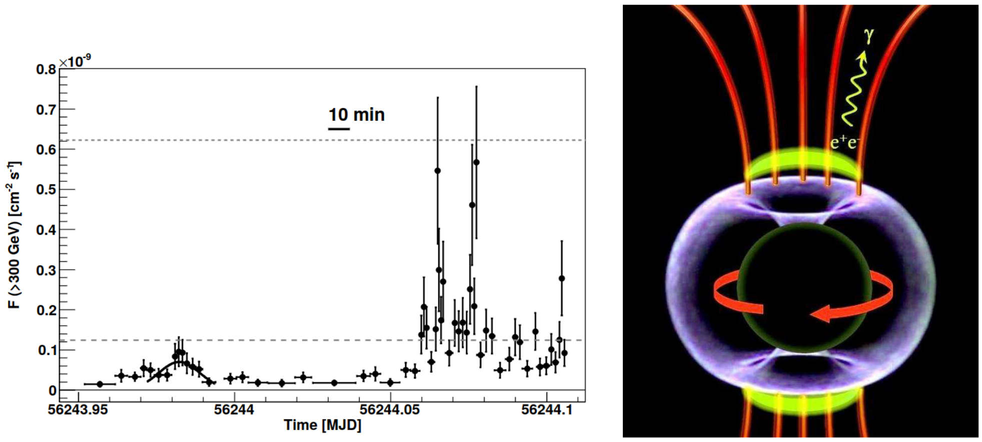
3.5. Extreme Sources

The BL Lacs that exhibit a synchrotron peak at unusually high energies, above 10^{17} Hz, belong to the EHBL class (extreme HBLs, [84]). EHBLs are expected to be very faint in the VHE gamma-ray range and very difficult to detect by IACTs. Nevertheless, their study is appealing as they can be used for testing the gamma-ray propagation at high energy and in particular to probe EBL and derive limits on the IGMF (inter galactic magnetic field, see [85] for a review). Ref. [86] reports in detail on the progress made in studying such AGNs. MAGIC has devoted many observations to the hunting and study of EHBLs.

In 2018, MAGIC observed and detected the EHBL 2WHSP J073326.7+515354 for the first time in the VHE gamma-ray range [28]. The observations were scheduled as part of MAGIC's hunting strategy for such extreme sources, and this source was chosen primarily because of its high synchrotron peak frequency ($\nu_{synch} = 10^{17.9}$ Hz). The successful strategy led to the VHE detection and to an in-depth study of the MWL properties of the SED. The theoretical interpretation of the broadband emission was challenging as expected for this type of AGNs, and four different theoretical models were used to test this particular case. The scenario that best described the dataset was a spine-layer two-zone leptonic model, as described in [87]. Many other EHBLs were observed by MAGIC as part of the EHBL hunting programme, and are collected in [25]. This work also includes the archetypal EHBL 1ES 0229+20 and the results of its observation from 2013 to 2017. Also included in [25] are three EHBLs detected for the first time in the VHE gamma-ray range: 1ES 2037+521, RBS 0723, and TXS 0210+515. Ref. [86] describes and emphasises the existence of two different types of EHBLs: extreme-synchrotron sources (synchrotron peak energy $= h\nu_{synch} \geq 1$ keV) and extreme-TeV sources (gamma-ray peak energy $= h\nu_{\gamma} \geq 1$ TeV). This difference corresponds to a hard spectrum in the soft X-ray band (photon index $\Gamma_{X-ray} < 2$), or in the TeV band ($\Gamma_{\gamma} < 2$). Blazars belonging to the HBL class can take on extreme properties and exhibit extreme behavior. This has been established on two occasions by MAGIC observations, for Mrk 501 [88] and for 1ES 2344+514 [89,90]. EHBLs, and in particular extreme-TeV sources, are perfect candidates for the study of IGMF, since their high energy emission and hard spectrum can be used to constrain the presence of cascades in the IGMF. For this reason, an in-depth study using gamma-ray observations (by MAGIC, H.E.S.S., VERITAS and the *Fermi*-LAT telescopes) of the archetypal EHBL 1ES 0229+20 was performed with the specific aim of detecting or constraining the IGMF-dependent secondary produced during the propagation of TeV gamma rays through the intergalactic medium. The results presented in [91] set robust limits consisting of a lower bound of $B > 1.8 \times 10^{-17}$ G for the long-correlation-length IGMF and $B > 10^{-14}$ G for an IGMF of cosmological origin.

3.6. Black-Hole Lightening: IC310

A very interesting result from MAGIC concerns the radio galaxy IC 310, which is powered by a supermassive black hole ($M = 3 \times 10^8 M_{\odot}$). In 2012, a high amount of activity of the source was observed in the VHE gamma-rays, characterized by a very fast variability (doubling time scales faster than 4.8 min). This result challenged the existing theoretical models of the variability and suggested a new interpretation of the sub-horizon scale variability consisting of a pulsar-like particle acceleration by the electric field across a magnetospheric gap at the base of the radio jet [92]. This interpretation is shown in Figure 4.



(**a**) (**b**)

Figure 4. (**a**) Light curve of IC 310, observed by the MAGIC telescopes in 12–13 November 2012. Reprinted from [92], Figure S4. (**b**) Emission scenario for the origin of the highly variable gamma-ray emission observed in IC 310 during the 2012 activity: the black sphere represents the rotating black hole with its event horizon accreting plasma from the center of IC 310. The apple-shaped blue form represents the ergosphere surrounding the black hole. The magnetosphere is shown in red and the polar vacuum gap regions in yellow. In the gaps, the electric field of the magnetosphere has a component that runs parallel to the magnetic field accelerating particles to ultra-relativistic energies. The observed gamma rays arise from inverse-Compton scattering and copious pair production due to interactions with low-energy thermal photons from the plasma accreted by the black hole. Reprinted with permission from [92], Figure S5.

3.7. Markarian Galaxies at VHE Gamma-Rays: Mrk 421 and Mrk 501

Two AGNs emitting in the VHE gamma-ray range, Mrk 421 and Mrk 501, belonging to the category of Markarians (AGNs named after Benjamin Markarian, who brought them into attention because of their uncommon excess of emission in the UV band), have been monitored by MAGIC since the beginning of the operations. Those close-by blazars (redshift z = 0.031 and z = 0.034, respectively) are perfectly suited to study the mechanism of acceleration and broadband emission of blazars for the following reasons: their proximity implies a negligible effect of EBL absorption on their VHE gamma-ray spectra and also very precise VLBI (Very Large Baseline Interferometry) studies that can be used to constrain the emission scenarios; their brightness allows monitoring in different activity states (quiescent, flaring and intermediate states) and consequently a study of the temporal evolution of their broadband SEDs; their variability can be used to break degeneracies between emission models.

MWL campaigns were organized to obtain simultaneous MWL data from Mrk 421 and Mrk 501. This has led to several works over the years describing the broadband emission of such powerful blazars over the years, accompanied by detailed studies of the broadband correlations and variability in different activity states, as shown in Tables 2 and 3.

All publications by MAGIC (in collaboration with many other instruments) on Mrk 421 and Mrk 501, together with the main results and the corresponding references, are listed in Tables 2 and 3. Another Markarian, Mrk 180, was discovered in the VHE gamma-rays by MAGIC in 2006 [26] during an optical outburst. This source is very faint has only been observed in the VHE gamma-ray range by MAGIC on this occasion.

Table 2. List of the main results obtained by MAGIC on Mrk 421.

Mrk 421			
Observational Period	**Main Results**	**Theor. Model**	**Ref.**
November 2004–April 2005	γ-ray/X-ray corr., IC peak $\sim$100 GeV	one-zone SSC	[93]
22–30 April + 14 June 2006	intra-night var. (29 April, $\sim$36 min)	leptonic	[94]
5 August 2008–12 March 2010	MWL SED in a quiescent state characterization	one-zone SCC, proton-synch	[95]
March 2010	γ-ray/X-ray corr., γ-ray and X-ray var.	one-zone SCC, two-zones SSC	[96]
January–June 2009	quiescent state characterization, X-ray harder-when-brighter, γ-ray/X-ray corr., optical/X-ray anti-corr.	one-zone SCC	[97]
January–March 2013	γ-ray/X-ray corr., double-bumped frac. var., low state characterization	one-zone SCC, suggestion of multi-zone leptonic	[98]
March 2007–June 2009	X-ray/soft X-ray corr., frac. var. increasing with energy, different levels of activity	suggested SSC, or generic hadronic scenarios	[99]
28 April–4 May 2014	X-ray spectrum variability	one-zone SSC	[100]
November 2014–June 2016	X-ray and γ-ray harder-when brighter, double-bumped frac. var., X-ray/γ-ray/ corr., VHE intra-night var. (27 January + 12 March 2015)	suggesting that the emission is powered by a multiplicative process	[101]
11–19 April 2013	intra-night var. of X-ray and VHE γ-ray bands, VHE γ-ray/X-ray corr.	magnetic reconnection in a multi-zone scenario	[102]
February 2010	limits on the Doppler factor and size of the emission region, time-lagged corr. optical/VHE	one-zone SSC excluded	[103]
December 2016–June 2017	VHE/X-ray corr., orphan γ-ray activity, intra-night VHE var., UV/X-ray anti-corr.	two-zone leptonic	[104]
December 2007–February 2009	upper limits on extended emission	possible constraints on EGMF	[105]

Table 3. List of the main results obtained by MAGIC on Mrk 501.

Mrk 501			
Observational Period	**Main Results**	**Theor. Model**	**Ref.**
May–July 2005	VHE intra-night var., spectra hardening when increasing flux, var. increasing with energy	one-zone SSC	[106]
July 2006	low state in VHE steep VHE photon index spectral hardening with flux (VHE)	one-zone SSC	[107]
15 March–1 August 2009	low activity characterization	one-zone SSC	[108]
March 2009	quiescent state characterization, X-ray peak shift of two orders of magnitude	one-zone SSC	[109]
1 April–10 August 2013	hard X-ray var. on hour timescales, five MWL SEDs	one-zone SSC	[110]
March–May 2008	low state characterization, hint of X-ray-to-VHE correlation	one-zone SSC	[111]
15 March–1 August 2009	frac. var. increasing with energy, flaring activity coincident with EVPA rotation (1 May)	two-zones SSC	[112]
March–July 2012	hard X-ray and VHE spectral indexes, extreme behaviour, VHE/X-ray corr., frac. var. increasing with energy	one-zone SSC	[88]
16–31 July 2014	frac. var. increasing with energy, VHE/X-ray corr., narrow feature in the VHE spectrum at 3 TeV (19 July)		[113]
February 2017–December 2020	X-ray/VHE corr., HE/radio corr.,	one-zone leptonic, two-zone leptonic, but also hadronic and lepto-hadronic are considered	[114]
May and April 2008	upper limits on extended emission	possible constraints on EGMF	[105]

3.8. Long-Term Monitoring Campaigns

Long-term monitoring of specific AGN targets has been a successful strategy that has yielded many results.

For example, the giant radio galaxy M 87 has been studied by MAGIC over the years allowing in-depth characterization of its quiescent states [115,116], and investigation of its flare activity [117,118]. Since M 87 is a very important target for radio observation, a collaboration in MWL with many telescopes, including EHT (Event Horizon Telescope, ref. [119]), enabled an in-depth MWK study of this close radio galaxy [116,120].

The blazar PG 1553+113 was also the subject of long monitoring campaigns in MAGIC. This blazar has been observed by MAGIC from the beginning of the operations in mono mode [121,122] and as part of MWL monitoring campaigns. Ref. [123] reports on 5 years of observations and the associated results. Recently, this source, already known for its variability in different energy bands, has been found to exhibit a quasi-periodicity in gamma-rays [124–126], making its monitoring even more important to shed light on the complex MWL emission mechanism.

The BL Lac object 1ES 0647+250 was discovered in 2012 as emitting VHE gamma-rays [127] by MAGIC. Following this finding, a monitoring campaign was launched to collect MWL data and investigate this HBL in detail. The campaign resulted in an in-depth study of the correlations between the wavebands and the characterization of the broadband emission in four different activity states [46]. Long-term variability was found in the X-ray and VHE gamma-rays band, as well as correlations between radio, optical and HE gamma-ray fluxes.

The blazar 1ES 1959+650 was detected by MAGIC in 2004 [128]. Blazar 1ES 1959+650 is a nearby AGN (z = 0.048) and an HBL that showed high activity in various energy bands in 2015, especially in the optical, but also in the gamma-ray range. The results of MAGIC and MWL monitoring of this source in recent years are summarised in [129]. These include the detection of intra-night flux variability in the VHE gamma-ray range and the interpretation of the broadband emission within a one-zone SSC model.

3.9. Multi-Messenger Studies

The first MM event in which photons and neutrinos were detected simultaneously from an astrophysical source was the famous explosion of supernova 1987A [130].

In the following years, the development of neutrino experiments made it easier to detect neutrinos from astrophysical objects and to identify their origin. This enabled a complex system of alerts in cooperation with other observatories and telescopes at different photon energies. The efforts of the astronomical community were rewarded when in 2018 when the blazar TXS 0506+056 was found to be flaring in many wavelengths in coincidence with the neutrino event IceCube-170922A. This important detection was made possible by the coordination between the instruments and the prompt response to the IceCube alert. MAGIC was involved in the MM observations and in this discovery, reported in [53]. Several theoretical models have been tested to explain the MM SED and in [54] the dataset is interpreted using a one-zone lepto-hadronic scenario in which the gamma-ray emission is produced by the inverse Compton up-scattering of external photons (see Figure 5).

Thanks to the close collaboration between neutrino experiments and other instruments across the electromagnetic spectrum, MM observations are carried out regularly to be prepared for the next MM event of a blazar.

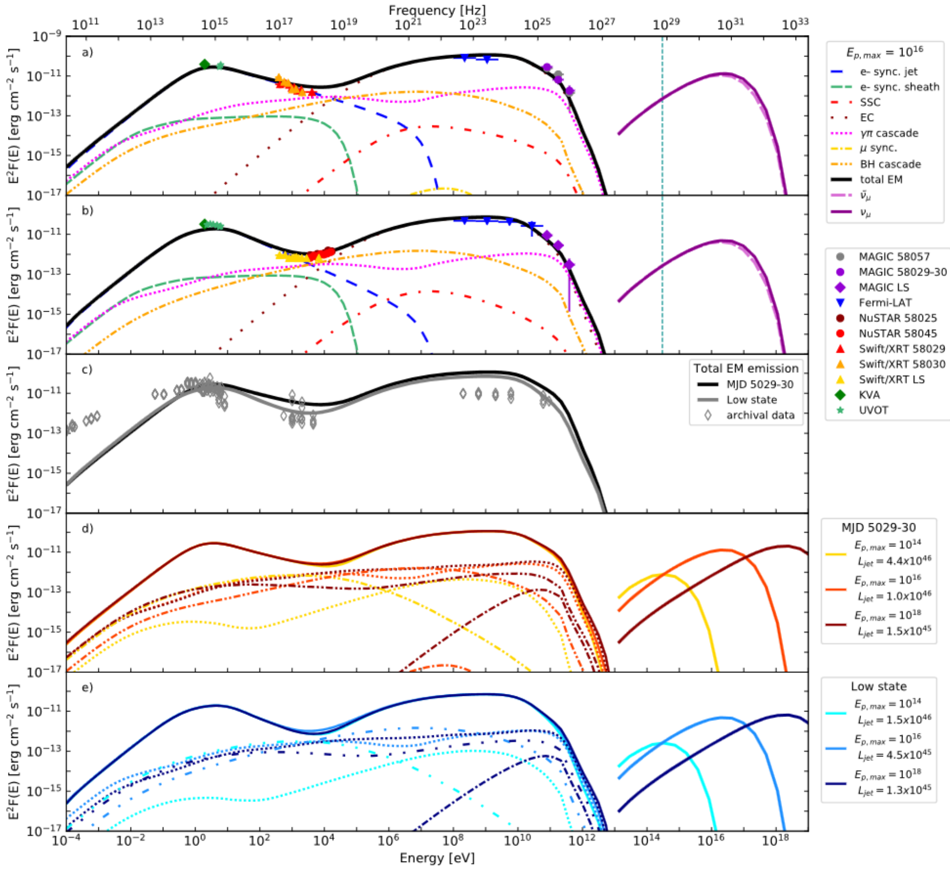


Figure 5. MM SEDs of the blazar TXS 0506+056. Panel (**a**) shows the MM SED for the enhanced VHE gamma-ray state, while panel (**b**) shows the MM SED for the lower state. Panel (**c**) shows a comparison with archival data, while panels (**d**,**e**) show results for different values of the maximum proton energy. Reprinted with permission from [54].

4. Broader Context: Other IACTs

Since MAGIC began the operations, other IACTs have also been active in the VHE gamma-ray field and have collected crucial results on AGNs and other targets. The present work is devoted only to the highlights of MAGIC, but it is important to consider the broader context of telescopes observing in a very similar energy range.

The VERITAS (Very Energetic Radiation Imaging Telescope Array System, ref. [131]) telescope array, which has been active since 2007, has observed and studied several AGNs as part of a dedicated AGN observing program [132]. The energy range of the VERITAS array extends from 85 GeV to 30 TeV. Scientific highlights of VERITAS are presented in [133] and listed on the VERITAS webpage (https://veritas.sao.arizona.edu/the-science-of-veritas/veritas-results; accessed on 12 January 2024). The VERITAS array is located in the Northern Hemisphere, like MAGIC, so many targets are common, allowing for joint publications and scientific collaboration in several cases (e.g., [88,97,100,103]).

The H.E.S.S. (High Energy Stereoscopic System) telescope array has been in operation since 2003. It is located in the Southern Hemisphere and has also studied several AGNs in the VHE gamma-ray range, from 30 GeV to 30 TeV. The highlights of their observations of AGNs are presented for example in [134,135]. A full list of scientific results can be found on their website (https://www.mpi-hd.mpg.de/HESS/pages/publications/, accessed on 12 January 2024). MAGIC has also collaborated with H.E.S.S. in the study of AGNs (e.g., [52,136]).

The FACT (First G-APD Cherenkov Telescope [137]), located at the same site of MAGIC, has been in operation since 2011 and its scientific program focuses mainly on the observations of extragalactic objects and in particular on the long-term monitoring of AGNs [138].

FACT observations can trigger follow-up observations with other IACTS with higher sensitivity, such as MAGIC, H.E.S.S. and VERITAS [88,89,104,113,139].

The LST-1 [140], which was inaugurated in 2018, is located at the same site of MAGIC (ORM observatory). This telescope, together with three others of the same design to be put in operation in the coming years, will form the group of LSTs [72] that will be part of the future CTAO (Cherenkov Telescope Array Observatory [141]). LST-1 has already achieved results in the observation of the gamma-ray source LHAASO J2108+5157 [142]. As for the study of AGNs, it has recently discovered the FSRQ OP 313 [73] in the VHE gamma-ray range. Collaboration with MAGIC in the observation of AGNs and other targets is planned, and joint data analysis will be possible thanks to a dedicated analysis pipeline [143].

5. Conclusions

The study of extragalactic sources has been one of the main targets of the MAGIC Florian Goebel telescopes for the last 20 years. The low energy threshold, which was the main goal behind their constructions (see Section 2.1), allowed a close connection to the other gamma-ray experiments and a smooth reconstruction of the high-energy bump of the MWL SEDs of many AGNs. In addition, it enabled the detection and discovery in the VHE gamma-ray range of two FSRQs close to redshift 1 (QSO B0218+357, Section 3.2.1 and PKS 1441+25, Section 3.2.2), at the limit of the IACT detection capacity, allowing the EBL to be studied for the first time at this distance with VHE gamma-ray measurements. Remarkably, of the only 10 FSRQs detected to date in the VHE gamma-ray range, six were discovered by MAGIC (See Section 3.3).

Thanks to the prompt response to MWL alerts under a dedicated ToO program, MAGIC discovered 36 AGNs in the VHE gamma-ray range (see Section 3.1) and characterized several types of AGNs in detail over the years, focusing on MWL and MM studies, which are of utmost importance for the identification of the broadband emission scenario. MAGIC was involved in the first MM observation of a neutrino blazar, TXS 0506+056, in which VHE gamma-rays were detected in spatial coincidence with the neutrino observed by IceCube (Section 3.9). The latter result suggested that blazars can be sources of high energy neutrinos and stimulated the development of theoretical models that can reproduce the MM SED.

The monitoring of AGNs such as Mrk 421 and Mrk 501, PG 1553+113, M 87, 1ES 0647+250, 1ES 1959+650 enabled long-term studies of correlations between different energy bands and variability (Sections 3.7 and 3.8).

The results obtained by MAGIC during its long operation lifetime will certainly be complemented and extended by the new generation of IACTs—the CTAO (Cherenkov Telescope Array Observatory [141]).

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Abbreviations

The following abbreviations are used in this manuscript:

AGN	Active Galactic Nucleus
AGNs	Active Galactic Nuclei
EBL	Extragalactic Background Light
LIDAR	LIght Detection And Ranging
MAGIC	Major Atmospheric Gamma-ray Imaging Cherenkov (telescopes)

IACTs	Imaging Atmospheric Cherenkov Telescopes
HE	High-energy
VHE	Very-high-energy
MWL	Multi-wavelength
MM	Multi-messenger
SED	Spectral Energy Distribution
FSRQ	Flat Spectrum Radio Quasar
BL Lacs	BL Lacertae type objects
f.o.v	Field of view
MJD	Modified Julian Date
ToO	Target of Opportunity
SSC	Synchrotron self-Compton

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