Results from the MAGIC Gamma-ray Telescope

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Abstract. Very High Energy (VHE) gamma-ray astronomy is today a well established and successful discipline. Among the major imaging air Cherenkov telescopes in operation, MAGIC, a 17 m single dish telescope, has reached the lowest energy threshold. This unique feature has allowed the discovery of VHE gamma rays from 3C279, the farthest blazar detected in VHE, as well as the first observation of the VHE pulsed emission from the Crab pulsar. In addition a number of galactic and extra-galactic sources have been discovered or confirmed. Moreover, MAGIC has constrained limits of the quantum gravity mass scale, the extragalactic background light and gamma ray fluxes from dark matter annihilation. In 2009 a second 17 m telescope, MAGIC-II, will start operation. The stereoscopic observation mode will improve the angular and energy resolution, reducing the background at the same time. All this will improve the sensitivity of the instrument by more than a factor two.

1. Gamma-ray astronomy and the MAGIC Telescope
Gamma-ray astronomy and in particular Very High Energy (VHE) gamma-ray astronomy, above 100 GeV, has a short history. Most of the VHE sources known today have been discovered only during the last 5 years. This is the result of the success of the current generation of Imaging Atmospheric Cherenkov Telescopes (IACTs) in operation at present. The MAGIC telescope, as part of this generation of IACTs, has contributed significantly to the present situation.

VHE gamma-rays can provide information about the astronomical objects that can accelerate charged particles and originate the Cosmic rays. Gamma-rays are produced after the interaction of the cosmic rays with matter or radiation, something that usually happens very close to the source of cosmic rays. This means that the gamma-rays are closely connected to the cosmic accelerators. The type of objects that can accelerate charged particles and produce gamma-rays includes galactic objects like Supernova Remnants (SNRs), Pulsar Wind Nebulae (PWNs), Pulsars, X-ray Binary Systems, Microquasars, Globular Clusters (GCs) and the galactic centre. It includes also extragalactic objects like Active Galactic Nuclei (AGN), Gamma Ray Bursts (GRBs) and Starburst Galaxies.

VHE gamma-rays can also be produced as decay products of heavier particles. Some models can explain the presence of dark matter in the Universe as concentrations of the lightest supersymmetric particle. A very attractive hypothesis suggests that the dark matter consists of neutralinos that can annihilate producing gamma-rays and neutrinos in the final state.

As neutral particles, gamma-rays can travel long distances without deviations by the galactic or extragalactic magnetic fields. On the other hand, gamma-rays suffer the absorption by the Extragalactic Background Light (EBL), limiting the distance to the sources that can be
detected. Lower energy gamma-rays can travel longer distances, hence the importance of a low energy threshold.

The Imaging Atmospheric Cherenkov technique uses the atmosphere as a calorimeter to detect the extensive air shower produced after the interaction of a VHE gamma-ray. The atmosphere provides the large detection volume needed to detect the small fluxes of individual sources. 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 Cherenkov photons and focus them to a camera where an image of the atmospheric cascade is formed. By analysing this image it is possible to obtain the incoming direction of the gamma-ray and the energy. The analysis of the images is also used to reject the much higher background of cosmic rays initiated showers. In those cases, a hadron initiates the cascade in the atmosphere producing an image that can be easily distinguished from that of a gamma-ray in most cases.

1.1. The MAGIC Cherenkov Telescope

The MAGIC telescope is located on the Canarian island of La Palma at a height of 2200 m above sea level. As all IACTs the telescope consists of two main parts, the reflector dish and the camera (figure 1). The reflector dish has a parabolic shape and a diameter of 17 m (mirror area $234 \text{ m}^2$). It is currently the largest among the IACTs in operation in the world. The large reflector consists of 956 square mirror elements of 0.495 m × 0.495 m, spherical shape. The mirrors are made of AlMgSi alloy plates glued on aluminium honeycomb. Mirror reflectivity ranges from 80% to 90%, and showing very small degradation over time.

![Figure 1. Image of the MAGIC-I telescope in the canarian island of La Palma at a height of 2200 m above sea level. The reflector dish has a diameter of 17 m. The telescope structure is made of carbon-fibre tubes.](image)

The MAGIC camera is equipped with 577 high quantum efficiency photomultipliers. The photomultipliers have two different sizes, the 1” diameter tubes are located in the inner part of the camera and the 1.5” diameter tubes in the outer part. The photomultipliers have an enhanced QE optimised for the Cherenkov light spectrum. The signal from the photomultipliers is optically transmitted to the counting house where the trigger and the digitisation of the signal is applied. The signals are digitised with a 2 Gigsamples/second flash ADC that provides an excellent timing resolution. Thanks to that, the MAGIC telescope can reach a sensitivity of 1.6% Crab in 50 hours of observation above 270 GeV with only one telescope.

The 17 m reflector dish and the high quantum efficiency photomultipliers allow MAGIC to reach the lowest energy threshold among the IACTs: 55 GeV trigger threshold. Recently this value has been further improved by means of a novel trigger. The so called “sum trigger” has allowed MAGIC to lower the trigger threshold to only 25 GeV for some dedicated observations like the detection of the Crab Pulsar [4].
Since the start of the scientific observations in 2005, the MAGIC telescope has completed 3 successful observation cycles where an important number of scientific results have been obtained. They include the discovery or confirmation of a number of VHE gamma-ray galactic and extragalactic sources, as well as the constraint of models for the extragalactic background light, the quantum gravity mass scale and the mass of the lightest supersymmetrical particle in the case that this is the nature of the dark matter.

In the following sections, the main results obtained by the MAGIC telescope during the past 3 years will be summarised.

2. Galactic Sources
The MAGIC telescope has detected VHE gamma-ray emission from 10 galactic objects: The Crab Nebula, the Crab Pulsar, the Galactic Centre, HESS J1813-178, HESS J1834, the X-ray binary LSI 61+303, the microquasar Cygnus X-1, the dark accelerator TeV 2032+4130 and the SNRs IC443 and Cas A. Four of them (Crab pulsar, LSI 61+303, IC443 and Cygnus X-1) were observed for the first time by the MAGIC telescope. A brief description of some of the most important MAGIC discoveries follows.

2.1. SNR IC443
IC443 is an asymmetric shell-type SNR that has been detected in radio, x-rays and gamma-rays. The EGRET mission detected high energy emission centred in the shell of the SNR and not coincident with the X-ray pulsar CXOU J061705.3+222127. MAGIC observed the region for 29 hours and found an excess of 5.7σ at (6h 13m 6s, 22°31'48'') [1]. The MAGIC source is displaced to the south of the centre of the SNR shell and it is correlated with a dense molecular cloud and the location of MASER emission. The MAGIC VHE emission can be explained by π0 decay after the interaction of the cosmic rays accelerated in the SNR with the dense molecular clouds. Although a Bremsstrahlung origin of the gamma-rays can not be excluded, this hypothesis is difficult to reconcile with the radio, X-ray and optical emission towards the rim of the SNR and the EGRET source located towards the centre (figure 2).

2.2. X-ray binary LSI 61+303
This is a very interesting binary system containing a B0V main sequence star with circumstellar disk and compact object (black hole or neutron star) which displays periodic emission from radio
to X-rays. The best ephemerides are obtained from radio observations and show a periodic radio signal with a period of 26.4960 days. EGRET data showed a hint of periodicity in gamma-rays. The MAGIC experiment discovered for the first time the variable TeV emission from the system [2]. After the first discovery, MAGIC carried out a deeper observation of the object covering 4 orbital periods of the system. The total observation time is about 166 hours. The total lightcurve and the lightcurves for the individual periods are shown in figure 3.

MAGIC observations show that the gamma-ray emission from this object extends to at least 4 TeV. The TeV emission is periodic with a periodicity of 26.8 days, in good agreement with measurements at other wavelengths (figure 4). The peak of the emission is always found at orbital phases around 0.6-0.7. During December 2006 a secondary emission peak was detected at phase 0.8-0.9. An extensive multiwavelength campaign involving radio, X-rays and MAGIC observations was organised between October and November 2006. From these observations the existence of large scale persistent radio-jets can be excluded. A possible hint of X-ray and TeV correlation and evidence of radio and TeV non-correlation was also found.

![Figure 3](image)

**Figure 3.** VHE (E>400 GeV) gamma-ray flux of LSI 61+303 as a function of orbital phase. Four orbital cycles are shown and averaged over entire observation time (bottom panel).

### 2.3. Crab nebula and pulsar

The Crab Nebula is one of the best studied non-thermal objects in the sky. It is also the standard candle of VHE gamma-ray astronomy. Thanks to its low energy threshold, the MAGIC experiment has measured the Crab Nebula spectrum down to 60 GeV. From the spectral energy distribution MAGIC has also obtained the peak position of the Inverse Compton process at E=77±47 GeV [3]. Observations support the Synchrotron Self-Compton (SSC) model, however other models that involved bremsstrahlung and hadronic processes cannot be ruled out.

The Crab pulsar wind nebula is powered by the Crab pulsar (PSR B0531+21). The EGRET mission detected pulsed emission from the pulsar up to energies of ~10 GeV. Previous IACTs could not find statistically significant pulsations from the Crab pulsar, indicating that the pulsed emission should terminate below 100 GeV. The low energy threshold of MAGIC combined with the novel *sum trigger* that MAGIC developed, made possible to lower the MAGIC threshold to
Figure 4. Periodicity of the LSI 61+303 binary system in all measured wavelengths. Mean value of the period is about 26.5 days. Period of the system measured in VHE gamma-rays by MAGIC is 26.8±0.2 days.

only 25 GeV. From a total of 22 hours of observation, MAGIC could detect the Crab pulsar pulsation with a significance of 6.4σ. The MAGIC signal above 25 GeV is in phase with that of the EGRET (figure 5).

From the MAGIC measurement it is possible to obtain the cutoff energy of the spectrum, 16 GeV for an exponential cutoff and 21 GeV for a super-exponential cutoff. These values are a serious handicap for the commonly accepted polar cap model and favour the outer gap model.
3. Extragalactic sources

MAGIC has detected VHE gamma-ray emission from 14 objects in a redshift range that varies from \( z=0.0041 \) (the radio galaxy M87) to \( z>0.536 \) (the radio quasar 3C279). Seven of these objects have actually been discovered by MAGIC: a source in the 3C66A/B region, Mkn 180 \((z=0.045)\), BL Lac \((z=0.069)\), PG1553 \((z>0.25)\), 1ES1011+496 \((z=0.212)\), S5 0716+714 \((z=0.31)\) and 3C279 \((z>0.536)\). The four farthest objects detected by MAGIC has been actually discovered by MAGIC, which shows the importance of a low energy threshold to reach objects at larger distances.

In the following some selected results from MAGIC on extragalactic sources are reported.

3.1. VHE observations triggered by optical outbursts

MAGIC has pioneered the observation of blazars triggered by high flux states in the optical band. This strategy has been very successful since 3 objects has been discovered in the past 3 years: Mkn180 [5], 1ES1011+496 [6] and very recently S5 0716+714 [7]. Optical triggers come from the robotic KVA telescope (La Palma) operated by the Tuorla Observatory. 1ES1011+496 observation by MAGIC was triggered by an optical outburst in March 2007, resulting in 6.2\( \sigma \) detection above 200 GeV. In the case of S5 0716+714, the MAGIC observation was triggered in April 2008, resulting in 6.8\( \sigma \) in 2.6 hours above 400 GeV. 1ES1011+496 and S5 0716 are respectively the third-most and second-most distant TeV blazars after 3C279.

3.2. Gamma-rays from 3C279

3C279 is at present the most distant \((z=0.536)\) blazar detected in VHE gamma-rays. Gamma-rays are absorbed by interacting with the photons from the EBL when the energies involved reach the threshold of the electron-positron pair production. The gamma-ray absorption increases strongly with energy leaving its imprint on the energy spectra of distant sources (see section 4.1).

Magic discovered a flare from 3C279 on 23\(^{rd}\) February 2006, during a multiwavelength campaign on EGRET AGN 3C279. A marginal signal the 22\(^{nd}\) February was also observed. The signal detected yielded a significance of 5.77\( \sigma \) after trial corrections [8]. Measured spectrum can be fitted by a power law with differential index \( \alpha = -4.1 \pm 0.7_{\text{stat}} \pm 0.2_{\text{sys}} \) between 75 and 500 GeV (figure 6). During the MAGIC observation the source was in high optical state without indication of short term variability. This observation is the first gamma-ray detection of a Flat Spectrum Radio Quasar (FSRQ).

![Figure 6. Measured energy spectrum of 3C279. The grey area accounts for combined statistical and systematic errors. The triangles are measurements corrected by two models of EBL density (see section 4.1).](image-url)
4. Other MAGIC results

4.1. Extragalactic background light

The diffuse photon field accumulated during the star and galaxy formation history is commonly known as EBL. This radiation extends from the ultraviolet to far infrared and it is difficult to directly measure due to the strong foregrounds from our solar system and the Galaxy. The observation of VHE gamma-ray sources with IACTs provide an indirect measurement of the EBL that has proved to be very useful to constrain the EBL, specially in the range where EBL was not probed before. At present, the absolute level of the EBL density remains uncertain by a factor of 2 to 10.

As previously mentioned, the VHE gamma-rays can suffer absorption losses by interaction with the EBL photons. The optical depth for VHE gamma-rays is redshift and energy dependent. This makes the radius of the visible Universe in gamma-rays different for different energies. The lower the energy threshold of a VHE gamma-ray detector, the more distant are the visible sources. Independently of the distance, the EBL leaves its imprint on the observed VHE gamma-ray spectrum of all sources, making difficult to distinguish intrinsic source effects in the spectrum from the EBL effect.

Having access to a, now, large population of TeV blazars it is possible to derive some constraints on the effect of the EBL in the spectra and hence in the EBL density itself. Different authors assume that a spectral index of 1.5 to be the hardest possible intrinsic spectrum in the source. From there, limits to the EBL can be derived based on the observed blazar spectra in Earth. The detection of the radio quasar 3C279 by MAGIC has been used to improve the limits on the EBL photon density. VHE photons above 300 GeV were detected by MAGIC, lowering considerably the level of the EBL from previous predictions. Some models for EBL are clearly disfavour by the MAGIC measurement since they would require the source intrinsic spectrum to be harder than 1.5 as it is shown in figure 6.

![Figure 7. Spectral energy distribution of the EBL. Some of the EBL models are shown: Primack et al. in blue [10], Stecker et al. in red [11] and the limit derived from the MAGIC measurement in green [8].](image)

By finetuning a realistic EBL model in order to comply to the requirement that the intrinsic spectrum cannot be harder than 1.5, it was possible to derive an upper limit for the EBL [8]. The new upper limit probes for the first time the EBL at higher redshifts, in the range $0.2 < z < 0.5$ as can be seen in figure 7. In addition, the limit extends into the ultraviolet regime, being 0.2 to 0.8 $\mu$m a newly probed EBL region.

4.2. Quantum gravity

Quantum Gravity (QG) theories try to unify quantum and general relativity theories. QG theories require drastic modifications of the space-time structure as the energy of the particles approach that of the QG mass scale, often identified with the Planck mass.
$M_{\text{Planck}}=1.22 \times 10^{19}$ GeV. However QG theories may leave their imprint also at energies much below the QG scale. One possibility is an energy dependence of the speed of light in vacuum arising from the photon propagation through a gravitational medium containing quantum fluctuations on distances on the order of the Planck length. The space-time, smooth a long distances, may show a foamy structure at short distances inducing a time dispersion on the light travelling through vacuum. Lorentz invariance violation (LIV) is expected as a generic signature of approaches to QG [13].

On 30th June and 9th July 2005 the MAGIC telescope recorded two flares from Mkn 501 ($z=0.034$) that exceeded by about a factor 4 the flux of the Crab nebula. The flares exhibited also rapid flux change with doubling times as short as four minutes or less [12]. This was the first time that a short (≈20 minutes) VHE gamma-ray flare with a resolved time structure could be studied in detail. The two flares behaved differently: the June flare was only visible from 250 GeV to 600 GeV, the July flare was seen from 120 GeV to 1.2 TeV. These flares offered the possibility to search for QG effects using the GeV-TeV photons emitted during the flare. If photons at all energies are emitted simultaneously they should arrive Earth with a time delay which is energy dependent. The figure of merit for QG tests is given by the sensitivity to a given QG mass scale:

$$M_{QG} = \xi \frac{L}{c} \frac{E}{\Delta t}$$

$E$ is the photon energy, $L$ the distance travelled by the photons and $\xi$ is a model-dependent factor of the order 1 and $\Delta t$ is the delay relative to the standard speed of light.

The analysis of the June flare did not permit any conclusion on the time-spectral properties of the signal since the signal appeared only in the energy band from 0.25 to 0.6 TeV. The July flare, however, extends over a broader energy range and exhibits actually a delay of the higher energy photons. To establish the time delay of the photons two independent analysis were applied in [14]: an energy cost function and a likelihood function. Both analysis yield the same result, a delay of $(0.030 \pm 0.012)$ s/GeV. This delay corresponds to a lower limit of the QG mass scale of $M_{QG1} > 0.21 \times 10^{18}$ GeV at the 95% C.L. It can also be derived a limit in case of a quadratic dependence. In this case the quadratic delay is $(3.71 \pm 2.57) \times 10^{-6}$ s/GeV$^2$ and $M_{QG2} > 0.26 \times 10^{14}$ GeV at the 95% C.L., far beyond previous limits on a quadratic effect in photon propagation. The numbers could be turned into real measurements of the time delay due to QG effects in case that the acceleration mechanisms at source were understood and the observed delays were only due to propagation effects.

4.3. Dark matter searches

Different astronomical observations provide evidence for the existence of a new type of non-luminous, non baryonic matter. The so-called Dark Matter (DM) contributes to the total energy density of the Universe about six times more than baryonic matter. Weakly Interacting Massive Particles (WIMPs) are candidates for DM, with the lightest supersymmetric (SUSY) particle (neutralino) being one of the favourite WIMPs. Pairs of neutralinos can annihilate producing gammas in the final states. Unfortunately, direct annihilations into $\gamma \gamma$ or $Z \gamma$ are loop-suppressed and the expected gamma-ray spectrum from neutralino annihilation is continuous.

Good candidates for sources of gamma-rays from DM annihilation are Dwarf spheroidal galaxies (dSphs). These objects are characterised by a high mass to light ratio, implying a high DM concentration. The expected gamma-ray flux depends on the density distribution of DM in the object but also on the details of the SUSY model. Among these type of objects, MAGIC has look for gamma-ray emission from the Draco and the Willman-1 galaxy Dwarfs.

Draco is accompanying the Milk Way at a galactocentric distance of 82 kpc. The mass to light $(M/L)$ ratio is larger than 200. The short distance to the object and the high $M/L$ ratio makes
this object a good candidate for DM annihilation observations with MAGIC. Data were taken in May 2007 for an observation time of 7.8 hours \[15\]. No significant gamma-ray excess was found. An upper limit (2\(\sigma\)) above 140 GeV was computed assuming a point-like source and a spectral index of \(-1.5\) (typical for DM annihilation): \(\Phi_{2\sigma}(E > 140 \text{ GeV}) = 1.1 \times 10^{-11} \text{ photons cm}^{-2} \text{ s}^{-1}\). From this result it is not possible to constraint the mSUGRA phase space, but a very high flux enhancement can be excluded.

The dSph Willman1, discovered in 2004 by Willman et al. \[16\], is also a Milk Way companion. At the moment this object is the tenth dwarf spheroidal galaxy of the Milk Way and the first one discovered in ten years. It is located at a distance of 38 kpc and the corresponding M/L ratio is between 500 and 700. Willman was observed by MAGIC in May 2008 for more than 16.8 hours \[17\]. No significant excess above 100 GeV was found. In this case, upper limits were computed for different benchmark points defined in \[18\]. The different upper limits are in the order of \(10^{-12} \text{ ph cm}^{-2} \text{ s}^{-1}\), about 3 orders of magnitude above the model predictions. However, there are important uncertainties in the DM density profile or the presence of substructures in the dwarf galaxy. The whole parameter space was also not fully scanned.

At present, looking for gamma-rays from DM annihilation with MAGIC seems not very promising. However, the perspectives for the future are more positive. On one hand, the second telescope will improve the sensitivity of the instrument (see next section). On the other hand, the internal bremsstrahlung process, that was previously neglected, may enhance in some regions of the parameter space the production of VHE gamma-rays with typical energies above half of the neutralino mass. Moreover, fainter dSphs or new astronomical objects with higher DM density can be found. Finally, there is the chance that the Fermi gamma-ray telescope detects sources of gamma-rays that only IACTs could confirm as DM annihilation, since only they could reach the end of the photon spectra. Because of this in the next years, MAGIC or a new generation of IACTs could start excluding regions of the models parameter space.

5. The MAGIC-II stereoscopic system

After the successful operation of the MAGIC telescope, the MAGIC experiment will be expanded with the addition of a second telescope very similar to the first MAGIC telescope. The new telescope is located at a distance of 85 m from the first one and it is equipped with the same mirror diameter, as can be seen in figure 8. It has been build using the same technical innovations introduced in MAGIC-I, including: active mirror control, light carbon-fibre structure, optical signal transmission and fast signal digitisation. Main changes are concentrated on the camera where a larger trigger area and only one pixel size (\(0.1^\circ\) diameter) are used.

The second telescope will allow us to perform stereoscopic observations of the same air showers. This technique improves the reconstruction of the images because allows for a better three-dimensional reconstruction of the shower parameters. The background rejection is also improved by the improved reconstructed shower parameters and by the better source position reconstruction that uses the intersection of the images in the two cameras. Requiring the simultaneous trigger of the two telescopes also provides a natural reduction of the background level. With the two telescopes operating in stereo mode, a significant improvement of the performances is expected. The system of two telescopes will have a significantly improved sensitivity, a factor 2 to 3 (depending on energy) better than that of MAGIC-I. Angular resolution will be also improved by a factor around 2. In addition, the stereo mode will provide a significant reduction of the analysis threshold thanks to the reduced background level.

Currently the construction of the second telescope is finished and the telescope is in the commissioning phase. Scientific stereoscopic observations are expected to start during the first half of 2009.
Figure 8. Image of the MAGIC-II stereoscopic system. The second telescope (on the right) is currently in the commissioning phase. Scientific observations are expected to start during the first half of 2009.

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