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The MAGIC telescopes—Status and recent results

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Summary. — The MAGIC telescopes are two Imaging Atmospheric Cherenkov Telescopes located on the Canary island of La Palma. They provide the lowest energy threshold among the existing instruments of the kind, reaching down to 50 GeV in standard trigger mode. This allows us to close the energy gap between satellite-borne and ground-based gamma-ray observations for strong enough sources. During the first five years of monoscopic observations, many interesting results could thus be achieved. With the second MAGIC telescope, which started operation in 2009, the sensitivity could be improved by stereoscopic imaging, and 5 new detections could already be reported in 2010. We present the status of the MAGIC telescopes in 2010 and review the latest results obtained in mono- and stereoscopic mode. This includes, among others, the detection of the head-tail galaxy IC 310, a new multiwavelength study of Mrk 501, an updated lightcurve of the Crab Pulsar.

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1. – Introduction

The two MAGIC telescopes are presently one of the leading facilities for the observation of very-high energy (VHE, above hundreds of GeV) gamma-rays. They indirectly detect the gamma-rays by recording images of gamma-ray initialized particle cascades in the upper atmosphere, the so-called Cherenkov imaging technique. The location of the instrument is in the Roque de los Muchachos Observatory on the Canary island of La Palma (28.8° N, 17.8° W), at an altitude of 2220 m a.s.l.

Among the few other instruments of that kind, it is the one with the lowest energy threshold, reaching down to about 50 GeV, while still being sensitive up to several tens of TeV. This low energy threshold is a merit of several factors, among which the huge mirror dishes of 17 m diameter, the fast (2 GHz) readout electronics and the altitude are the most prominent ones. Besides the lowest threshold, MAGIC is built using a light-weight carbon fibre telescope frame. This makes it the fastest telescope concerning repositioning to a given direction in the sky. It allows for an 180° turn within about 20–40 s, which is essential for observations of Gamma Ray Bursts (GRBs).

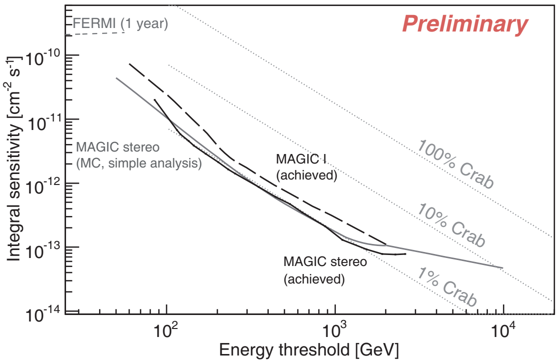

Fig. 1. – MAGIC integral sensitivity in Phase I (mono) and II (stereo), estimated from 3.5 h of Crab Nebula data. The achieved sensitivity for Phase II are better than the prediction mainly because they exploit fully optimized reconstruction algorithms that were not available at the time the MC was produced.

The operation of MAGIC started in fall 2004, using only the MAGIC-I telescope (MAGIC Phase I). It was complemented by a second telescope which became fully operational in late 2009 (Phase II). The stereoscopic observation of the particle showers improves the performance of the system, and lowers the systematic uncertainties. As a benefit of our improved performance, 5 new extragalactic VHE sources could already be reported in 2010(1).

2. – Performance

A detailed paper about the MAGIC performance in stereoscopic mode is in preparation. The following numbers may hence still be subject to minor changes and should be considered preliminary. A detailed description of the monoscopic performance is given in [1].

Figure 1 shows the sensitive range of monoscopic Phase I observations, and the predicted and achieved sensitivity for the stereoscopic Phase II. Here, the sensitivity is expressed as the source flux that is detectable with $5\,\sigma$ confidence within 50 hours of data taking at low zenith angle. The expected sensitivity was derived from a Monte Carlo simulation (MC). From Phase I to Phase II, it improved from 1.6% to less than 1% of the Crab Nebula flux, which means up to 60% less required observation time for the same detection.

The energy resolution above 300 GeV, defined as RMS, improved from 25% in phase I to 15% in phase II. The 39% directional resolution (*i.e.* Sigma of a 2D Gaussian function) at these energies could be improved from 0.1° to $< 0.07°$. This, along with the better gamma/hadron separation in stereoscopic mode, reduces the background by about a factor of 3, which leads to the above improvement in sensitivity and also leads to smaller systematic uncertainties, especially at low energies. It allows us to image the Crab Nebula even at energies around 80 GeV (see fig. 2), where the angular resolution is still about 0.15°.

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(1) `http://www.astronomerstelegram.org`

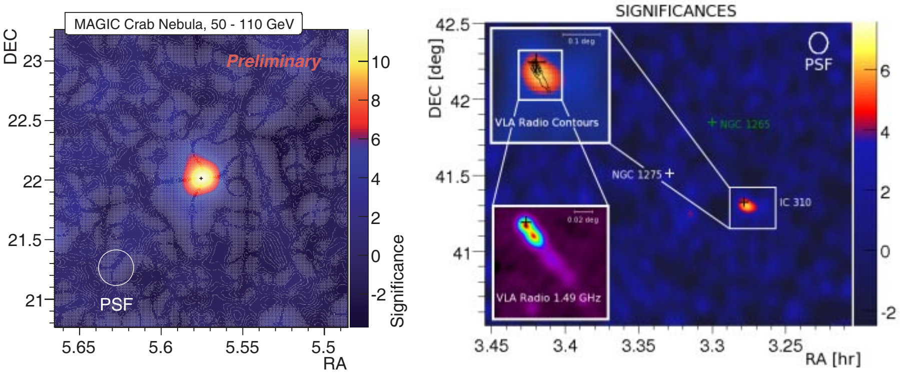

Fig. 2. – Left: low energy skymap of 2.6 h of Crab Nebula data below 30° zenith angle. The plot was done from events with reconstructed energies below 100 GeV, leading to a range of true energies of about 50–110 GeV (median 80 GeV). The PSF circle shows the 39% resolution, see text. Right: significance skymap of the IC 310 region for energies above 400 GeV, in comparison to radio contours from NVSS (see [6] for a detailed discussion and references).

3. – Scientific scope and selected recent results

MAGIC has a wide field of scientific targets, only few of which can be briefly presented in these proceedings. The topics that cannot be discussed in the following review include for example the flux upper limits derived for gamma-ray bursts (see, *e.g.*, [2]), possible dark matter annihilation spots in dwarf spheroidals [3] and galaxy clusters [4], and the globular cluster M13, which yielded interesting constraints on the density and/or efficiency of its pulsar population [5]. A complete list of publications can be found on the MAGIC website(2).

3˙1. *Extragalactic observations.* – Being on the northern hemisphere, MAGIC is ideally located to observe the gamma-ray emission of extragalactic objects. Most of these are Active Galactic Nuclei (AGN) of different kinds. One of the first sources MAGIC discovered in stereoscopic mode is the head-tail radio galaxy IC 310 [6] (fig. 2). It was detected in 20.6 h of observations taken between 2009 October and 2010 February. The observed Spectral Energy Distribution (SED) is remarkably flat, (photon index $\gamma = -2.00 \pm 0.14$), and there are clear hints for short-scale variability. This result favours the VHE emission to originate from the inner jet, close to the central engine of the AGN. The wide, flat spectrum furthermore challenges simple Synchrotron Self-Compton (SSC) models, favouring more complex or hadronic models for the emission mechanism.

For strong, established AGNs, MAGIC is frequently participating in large, synchronized MultiWaveLength (MWL) campaigns, organized on long terms between many observatories worldwide. Figure 3 gives an example SED from a MWL campaign on Mrk 501, taken during 4.5 months in 2009 [7]. This radio to TeV campaign provided the most detailed SED yet collected for that source. A multi-frequency SED allows for a deeper understanding of a source—in this case, the SED is well described by a one-zone SSC model, with an emission region $\leq 0.1\,\mathrm{pc}$ and an electron population with two spectral breaks.

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(2) `http://wwwmagic.mppmu.mpg.de`

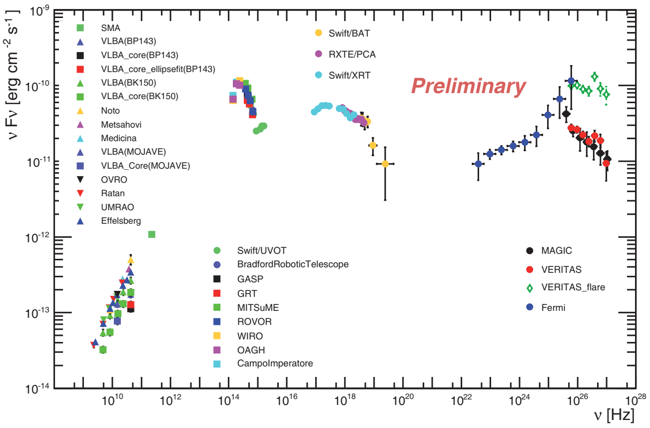

Fig. 3. – Spectral energy distribution of Mrk 501 averaged over all observations taken during the MWL campaign performed between 2009 March 15 and 2009 August 1. The TeV data from MAGIC and VERITAS have been corrected for the absorption in the extragalactic background light (find details on this, and further references, in [7]).

Two complementary topics to the above are the study of the extragalactic background light (EBL) and the ExtraGalactic Magnetic Field (EGMF). The EBL, mainly comprising diffuse light from stars and dust, leads to the absorption of gamma-rays above few hundreds of GeVs. The sub-100 GeV threshold of MAGIC however allowed us to detect the most distant VHE AGN [8]. With few basic assumptions about plausible intrinsic emission spectra, we could exclude several EBL modelings, showing that the universe is more transparent than was previously assumed.

Testing the emission from AGNs for a possible extended halo was recently shown to probe the strength of the EGMF [9]. As described there, VHE gamma-rays from AGNs may undergo interactions in the extragalactic space between the AGN and ourselves that produce intermediate charged particles and secondary gamma-rays. If the EGMF has a strength of few 10^{-15} G, the charged particles may both live long enough and be deflected enough to mimick a gamma-ray halo around the otherwise point-like source. The fact that such a halo was not found beyond uncertainties suggests that the strength of the EGMF must either be well above or below the value of few times 10^{-15} G.

3˙2. *Galactic observations.* – Galactic targets of observations of MAGIC include pulsars, Pulsar Wind Nebulae (PWN), supernova shells, binary systems and magnetars. Due to its low threshold, MAGIC-I is the only Cherenkov telescope to date that detected pulsed gamma ray signals from a pulsar. The mere fact of detecting pulsed emission above 25 GeV from the Crab pulsar [10] already ruled out emission models in which the pulsed component is produced anywhere near the pulsar surface, because the strong magnetic field would simply absorb such highly energetic radiation by invoking electron pair production. Figure 4 shows an updated light curve from 59.1 h of data collected between 2006 and 2009. The excess events of the two peaks are $(6.2 \pm 1.4) \times 10^3$ for P1 and $(11.3 \pm 1.5) \times 10^3$ for P2, corresponding to $4.3\,\sigma$ and $7.4\,\sigma$, respectively.

In 2009, we took 25.5 hours of good-quality monoscopic data in the region of supernova remnant G65.1+0.6. The area hosts the two GeV sources 1FGL J1954.3+2836 and 1FGL J1958.6+2845, both of which were reported to have a multi-TeV counterpart detected in Milagro data [11]. From our observations, we could extract upper limits on

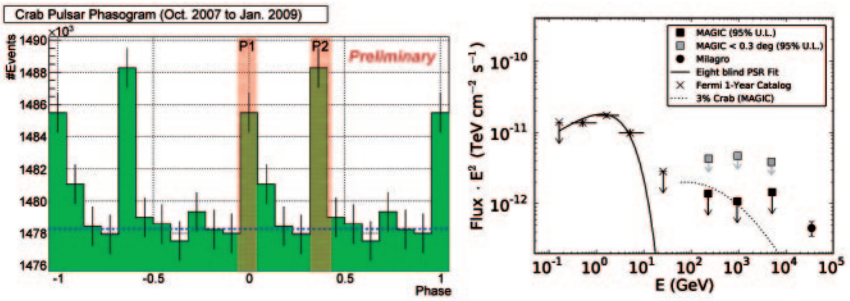

Fig. 4. – Left: phaseogram of the Crab pulsar, obtained from 59.1 h of good quality data, using only Cherenkov images with and integral size between 25 and 500 photo electron equivalents, roughly corresponding to energies above 25 GeV. Right: differential flux upper limits for the region around 1FGL J1954.3+2836, in the context of the Fermi and Milagro flux estimations (see [12] and references therein).

the 2–3% Crab Nebula flux level [12] (fig. 4). This supports the idea that the Milagro emission emerges from old and/or high-peaked PWN, similar to what was found for several other Milagro-detected Fermi bright sources. Other recent MAGIC-I upper limits of PWNe can be found in [13].

Another kind of gamma-ray emitter are binary systems. One of them is the X-ray binary LS I +61 303, for which MAGIC conducted a multiwavelength campaign with XMM-Newton and Swift during 60% of an orbit in 2007 September. A simultaneous outburst at X-ray and VHE bands was detected, as shown in fig. 5 [14]. The simultaneity, and the extracted X-ray/VHE flux ratio, suggested that, for this outburst, the X-rays are the result of synchrotron radiation of the same electrons that produce VHE emission as a result of inverse Compton scattering of stellar photons.

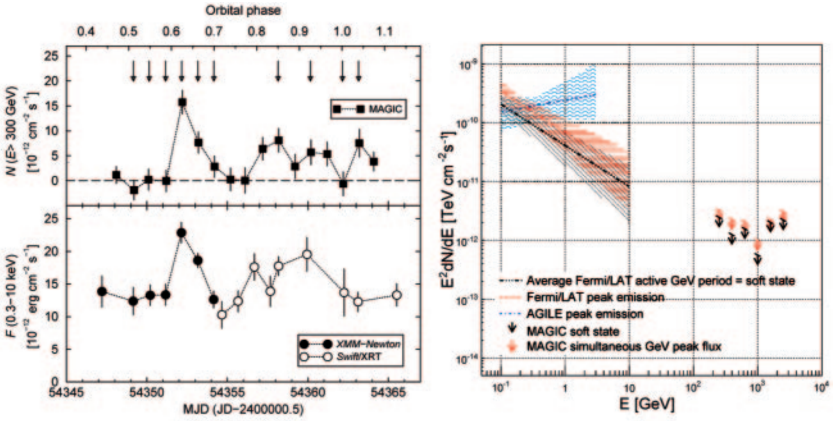

Fig. 5. – Left: VHE gamma-ray and X-ray light curves of LS I +61 303 during the multiwavelength campaign of 2007 September. Right: Cygnus X-3 SED in the high-energy and VHE bands. The lines indicate the power law spectra derived from Fermi/LAT and AGILE integral fluxes and photon indices, where the corresponding errors were taken into account and are shown in shadowed areas. The arrows display the 95% CL MAGIC differential flux upper limits.

Cygnus X-3 is a microquasar consisting of an accreting compact object orbiting around a Wolf-Rayet star. It has been detected in gamma-rays above 100 MeV by the Fermi [15] and AGILE [16] satellites and many models also predict a VHE emission when the source displays relativistic persistent jets or transient ejections. MAGIC observed Cygnus X-3 for about 70 hours between 2006 and 2009 in different X-ray/radio spectral states and also during a period of enhanced gamma-ray emission [17]. No signal was found, and the most stringent upper limits to date were extracted for different spectral states, orbital phases, energies, and dates. Figure 5 shows the SED for different spectral states.

4. – Upgrade plans

In 2011, the MAGIC telescopes will be upgraded. The goal is to make the two telescopes more similar, and thus achieve a more homogeneous exposure. The main targets of the upgrade include a complete replacement of the MAGIC-I camera, equipping it with an equally large number of pixels (1039) and an equally large trigger area. Besides that, both telescopes will get a new readout readout based on Domino-4 ring samplers(3) and new low-energy specialized SUM-trigger systems.

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(3) `http://drs.web.psi.ch`