Frascati Physics Series Vol. 58 (2014)
Frontier Objects in Astrophysics and Particle Physics
May 18-24, 2014

THE MAGIC LEGACY TO NEXT GENERATION OF IACTS: RESULTS, RECENT HIGHLIGHTS AND PROSPECTS

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Abstract

The present generation of Imaging Air Cherenkov Telescopes (IACTs) has greatly improved our knowledge on the Very High Energy (VHE) side of our Universe. The MAGIC IACTs operate since 2004 with one telescope and since 2009 as a two telescope stereoscopic system. I will outline a few of our latest and most relevant results: the surprising gamma-ray factory in the Perseus galaxy cluster with emission from NGC 1275 and the puzzling emission of IC 310; the advances on the identification of the location of emission region in jets of AGNs; the discovery of pulsed emission from the Crab pulsar at VHE, recently found to extend up to 400 GeV and along the "bridge" of the light curve. The results that will be described here and the planned deep observations in the next years will serve as a sound cornerstone for the future of VHE Astrophysics.

1 The MAGIC telescopes

The two MAGIC IACTs were built and are currently operated by a collaboration of institutions in Bulgaria, Croatia, Finland, Germany, Italy, Poland, Japan, Spain, and Switzerland [1].

MAGIC is located at the Roque de los Muchachos Observatory in the island La Palma (Spain). The first single telescope (MAGIC-I) started operations in 2004 and was at the time the largest IACT yet constructed (17m diameter mirror), a fact which translated into a very low energy threshold for VHE γ-ray detection. MAGIC-I featured significant novelties in IACTs, such as the fastest sampling of Cherenkov signals (2 GSps) or active mirror control. Its ultralight carbon fiber frame and mirrors enable very fast repositioning of the telescope (<20 secs for half a turn), a crucial fact to study the prompt emission of GRBs.

The introduction of a second telescope, MAGIC-II, enabled the instrument to perform stereoscopic observations with significantly better sensitivity, and angular and spectral resolutions, starting in Fall 2009. As of today the MAGIC telescopes remain the IACT array with the largest mirrors in the world. MAGIC-II was built essentially as an improved copy of MAGIC-I. The main difference between the telescopes were their cameras and their readout electronics. MAGIC I camera was composed of 577 pixels of two different sizes. On the contrary, the MAGIC II camera was built with 1039 pixels of the same size (0.1°). The readout sampling speed was 2 GSps for both telescopes, but using very different electronics.

During the Summers of 2011-2012 the instrument experienced a thorough upgrade [1)]: the readout was replaced by a homogeneous system based on the DRS4 analog memory sampling chip, a clone of the MAGIC-II camera and L1 trigger were installed in MAGIC-I. The upgrade of the MAGIC-I trigger results in an enlarged trigger area for the system. Besides, since both telescopes are now essentially identical, maintenance and operation are easier.

The threshold energy (peak of the energy distribution of stereo recorded events) of the upgraded telescope has been estimated to be 50 GeV. Fig. 1 shows the sensitivity of the instrument as a function of energy. For energy

[1] An updated list of collaboration members can be found at *http://magic.mpp.mpg.de*

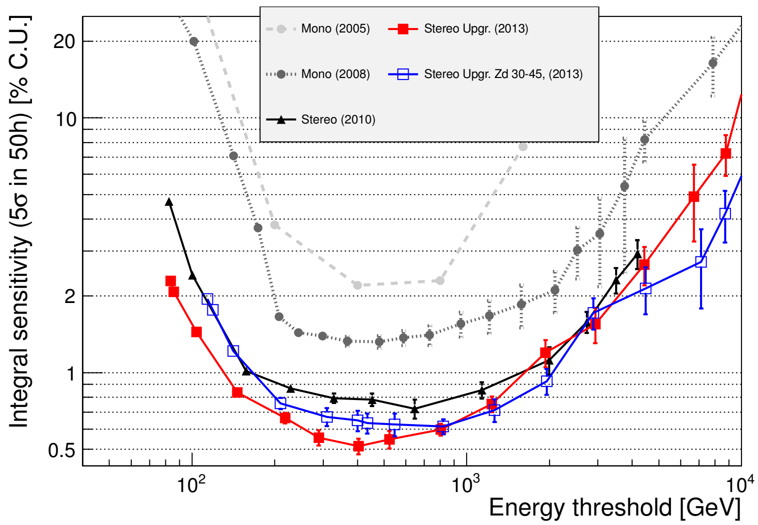

Figure 1: *Integral sensitivity of the current MAGIC Stereo system and previous experimental setups, defined as the flux for which* $N_{\rm excess}/\sqrt{N_{\rm bgd}} = 5$ *after 50 h, and calculated using Crab data. From* [2].

above 300 GeV the sensitivity is 0.76% Crab units. There is a good agreement with the predictions from MC. Respect to single telescope observations, a factor ∼2 improvement in significance is achieved at a few hundred GeV and up to a factor ∼3 at lower energies. The differential sensitivity remains acceptable (10% Crab units) below 100 GeV. Stereo observations result in a significant improvement both in angular and spectral resolutions. An angular resolution of 0.07° is reached at 300 GeV. The best spectral resolution of 16% is reached at a few hundred GeV. Find more details about the instrument's performance in [2].

2 Extragalactic VHE γ-ray physics: not only blazars

Clusters of galaxies are the largest bound structures in our Universe. They are young: in fact they are still forming now. A huge energy budget is available from gravitational potential of infalling gas (about $10^{61} - 10^{63}$ erg). The observed synchrotron emission in the centers of clusters come from Cosmic Ray (CR) electrons, which are probably accompanied by 100 times more CR protons, because protons are easier to accelerate (as observed in our own galaxy). CR electrons may actually come from CR protons. The density of CR protons inside clusters may be measured using IACTs because CR protons produce γ-rays through π^0 decay.

MAGIC selected the Perseus cluster of galaxies for observations on account of the fact that it is nearby (78 Mpc), i.e. bright in X-rays, and shows a massive cool core and a radio mini-halo. Perseus was not detected at TeV energies after 85 hours of observations [3)]. We could set upper limits (ULs) at E>600 GeV. These ULs can be compared to cosmological hydrodynamical simulations with and without the contributions of individual galaxies or to the absolute minimum possible flux assuming that CR electrons are produced by CR protons. They are at the limit of the predictions of the simulations and a factor 3 above the the minimum flux. This allows to estimate the ratio of pressure applied by the CR and pressure produced by the thermal component of the cluster. It is as low as 0.77% - 11.6%. it also enables to limit the magnetic field B in the center of the cluster to B>4-9 μG.

Radiogalaxies (active galaxies displaying a radio jet) generate CR (electron or proton) bubbles in the intergalactic medium. The same process injects magnetic field into the intracluster medium. The total injected energy is huge ($10^{60} - 10^{61}$ erg): it represents a few % of the total energy of accretion into the central supermassive black hole. Relativistic electrons produce synchrotron which can be studied using radiotelescopes, but they also produce VHE γ-rays through Inverse Compton.

In fact radiogalaxies are interesting VHE sources because the emission is not so strongly beamed, i.e. the jet is not as aligned with the line of sight as in blazars, and because they are nearby objects, i.e. we can study them in more detail. IACTs have discovered four radiogalaxies at VHE: Cen-A, M 87, NGC 1275 and IC 310. MAGIC has discovered the last two sources, which actually belong to the same cluster of galaxies: Perseus.

MAGIC, together with HESS and VERITAS, has studied one of the other VHE radiogalaxies: M87. M87 is so close to us (17 Mpc) that many features in the jet can be resolved at longer wavelengths. Flux variations then allow to identify the source of the VHE emission: IACTs detected in 2007 a bright flare that was simultaneous to the brightening of the radio core [4)], indicating that VHE emission originates in the radio core. Unfortunately subsequent simultaneous observations have not shown a similar emission pattern [5)].

MAGIC discovered the radiogalaxy IC 310 at VHE [6)] during observations of Perseus. A flare was observed in 2011 which revealed that the source is variable from day to day [7)]. The observation of a second flare in 2012 showed even faster variability with time scales of 1-10 minutes [8)]. Even faster variability has been observed in blazars like Mrk 501 and PKS 2155304, but emission in blazars is doppler-shifted by a larger factor than in a radiogalaxy like IC 310 for which the largest allowed Doppler factor is around 4. The intrinsic variability of the source may in fact be so fast that the emission region is smaller than the event horizon light-crossing time. Hardly any model can accomodate such a small emission region.

3 Pulsars and pulsar wind nebulae

At VHE we study the particles with the highest energy which a pulsar is able to accelerate. MAGIC discovered emission at >25 GeV from the Crab pulsar [9)]. VERITAS discovered that the pulsed spectrum extends to >100 GeV [10)]. Some months later, MAGIC measured the spectrum of both peaks up to 400 GeV [11)]. MAGIC has recently discovered emission from the "bridge" of the light curve at energies exceeding 100 GeV [12)]. The presence of the bridge and the fact that both peaks are very narrow is hard to explain within existing models. Aharonian et al [13)] for instance propose that VHE γ-rays are not produced inside the magnetosphere but in the wind region. If true, VHE observations would allow to study the wind, which is totally dark at other wavelengths. This model is successful in producing bridge emission but predicts much broader peaks than those measured by MAGIC. Hirotani [14)] may be able to reproduce the shape of the light curve assuming that there is an additional toroidal component in the pulsar's magnetic field.

The largest population of sources in the HESS galactic plane survey are Pulsar Wind Nebulae (PWN). Energetically speaking pulsars are CR sources, that is, they spend most of their rotational power in accelerating particles. Photons, especially E<100 MeV, may well be considered as a "sideshow". MAGIC has only detected two PWN at VHE: Crab and 3C 58. These are however extreme PWN. Crab is the brightest PWN, while 3C 58 is the weakest and least luminous. They are both the least efficient VHE PWN. 3C 58 has in fact a γ-ray luminosity which is as low as 10^{-5} of the pulsar spindown power.

The latest MAGIC spectrum of the Crab Nebula is based on a 70 hour stereo observation spanning from 2009 to 2011 [15]. It extends from 50 GeV up to 30 TeV, with a statistical precision as low as 5% at E<100 GeV. Combined with the Fermi-LAT data, these data yield the most precise measurement of the IC peak so far, at (52.5±2.6) GeV (statistical error only).

The spectrum has been fitted to two different models. A static, constant B-field model [16] predicts however too broad an IC peak. Most probably this implies that the assumption of the homogeneity of the magnetic field inside the nebula is incorrect. A time-dependent model [17] is successful in reproducing the spectral shape under the assumptions of a low magnetic field of less than hundred μG. However, this model fails to provide a good fit of the new spectral data if the observed morphology of the nebula.

3C 58 is a PWN centered in PSR J0205+6449, one of the highest spin-down pulsars in the sky (Edot=2.7×10^{37} erg s^{-1}, or 2% of the Crab pulsar's Edot). The distance and age of this PWN are controversial. The distance may range between 2 and 3.2 kpc. It may be very young and associated to the historical supernova SN1181 or as old as 7000 years. The X-ray thermal emission from the central objects seems to be too weak for a neutron star in this range of ages [18], so it has been speculated that it may not be a simple neutron star, but contain a more exotic sort of matter. Like Crab it shows a torus and a jet in X-rays. Fermi-LAT detected pulsed emission at E<4 GeV and steady emission up to ∼100 GeV.

MAGIC has discovered 3C 58 at VHE after a 85 h observation [19]. Its flux is 0.65% crab, the weakest PWN detected at these energies. For existing models, only a short distance of 2 kpc or a high IR density can reproduce the data from radio to VHE (see Fig. 2). The IR density is probably unrealistically high, so the distance of 2 kpc is favored. The derived magnetic field by all the models fitting the γ-ray data is in any case smaller than 35 μG, very far from equipartition.

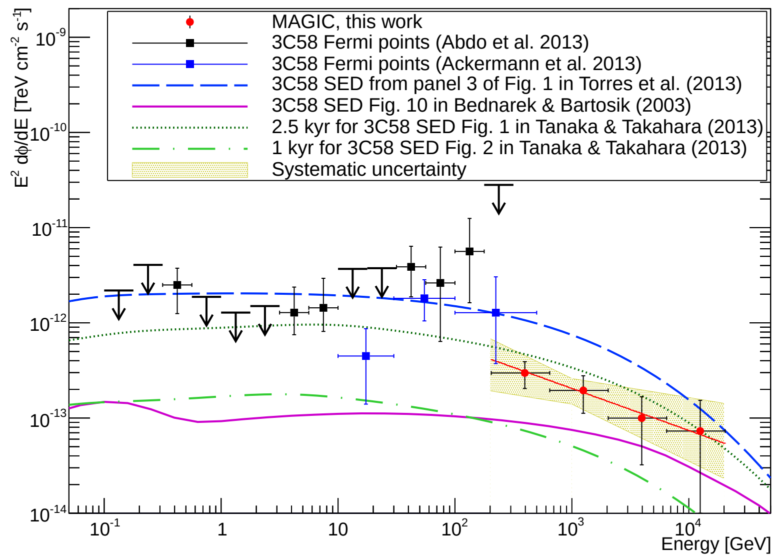

Figure 2: *3C 58 spectral energy distribution in the range between 0.1 GeV and 20 TeV. Red circles are the VHE points reported in this work. The best-fit function is drawn in red and the systematic uncertainty is represented by the yellow shaded area. Black squares and arrows are taken from the Fermi-LAT second pulsar catalog. Blue squares are taken from the Fermi-LAT high-energy catalog. The magenta, clear green dashed-dotted, dark green and blue dashed lines correspond to different models of the source. See* [19] *for details.*

4 Prospects

These were just a few of the latest results of MAGIC. Especially interesting are also the latest constraints on γ-ray emission produced by dark matter annihilation in the dwarf spheroidal Segue [20] or the recent multiwavelength study of PKS 1424+240, which may be the farthest AGN detected at VHE [20].

We plan to operate the telescopes during the next few years, for sure until the first CTA telescope start to operate. Since the current generation of IACTs have already studied most of the obvious candidates for VHE emission, future observations will probably go deeper into relatively few objects. In the last years we have setup a program of Key Observation Projects to identify and observe the most promising targets.

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