Gamma-ray, particle and exotic physics at TeV energies with the MAGIC telescopes

Original Citation:

Availability:
This version is available at: 11577/3253015 since: 2017-12-13T12:04:44Z

Publisher:
Editrice Compositori s.r.l.

Published version:
DOI: 10.1393/ncc/i2017-17115-5

IL NUOVO CIMENTO **40 C** (2017) 115
DOI 10.1393/ncc/i2017-17115-5

Colloquia: SciNeGHE 2016

Gamma-ray, particle and exotic physics at TeV energies with the MAGIC telescopes

M. Doro
Università e Sezione INFN - Via Marzolo 8, I-35131 Padova, Italy

received 21 April 2017

Summary. — MAGIC is an instrument composed of a pair of telescopes for gamma-ray and cosmic-ray astrophysics in the TeV range. It is operating for more than a decade now, and is one of the current best performing instruments in this field, specifically at low energies, where it achieves the largest sensitivity. MAGIC pursues a strong program in galactic and extragalactic gamma-ray science. Its catalog of blazars, radiogalaxies and galaxy clusters observations as well as supernovae, novae, pulsar wind nebulae, pulsars and binary systems has now increased to several tens of detected targets. In addition, MAGIC is suited for cosmic ray searches, being sensitive to the signatures of earth-skimming tau-neutrinos, cosmic antiprotons, and others. Furthermore, MAGIC has a strong fundamental physics program, with searches for particle dark matter, Lorentz Invariance violations, axion-like particles and primordial black hole evaporation, providing important recent constraints in some relevant cases. Finally, MAGIC has a follow-up program of Gravitational Waves events. Few highlights topics will be discussed in this contribution.

Introduction

MAGIC (Major Atmospheric Gamma-ray Imaging Cherenkov) is a telescope composed of a couple of 17 m diameter reflector of the IACTA (Imaging Atmospheric Cherenkov Telescope Array) class. The technique is based on the observation of the Cherenkov radiation generated in extended particle showers produced in the atmosphere by either cosmic particles of high energy cosmic radiation reaching the Earth. The sampling of the Cherenkov radiation guarantees good sensitivity, low energy threshold, good energy and angular resolutions, compared to shower-front particle detectors, at the expense of a duty cycle limited to dark or moderate moonlit nights. MAGIC is located at the Canary Island of La Palma (Spain), in the northern hemisphere, at the Observatorio de Roque de Los Muchachos, which will be soon hosting the new IACTA generation of the CTA project. The energy working range is 50 GeV to 50 TeV, with a sensitivity of 0.66% of the Crab Nebula flux above 220 GeV in 50 h [1] and the instrument is in operation for a decade now.

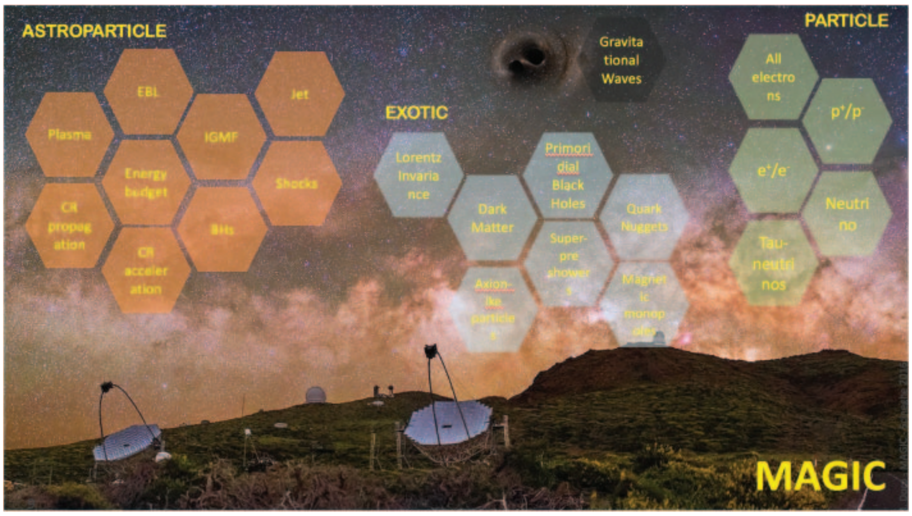

Fig. 1. – Science cases with very high energy gamma rays with MAGIC.

The MAGIC science program is wide (see fig. 1), and focused on VHE gamma-ray astrophysics. This encompasses relativistic jets physics, plasma physics, magnetic reconnection, diffuse shock accelerations, cosmic ray transport and so on, requiring often strong interdisciplinarity. The science pursues can be done in multiple galactic and extragalactic targets and target classes. This will be discussed in sect. **1**. However, with non standard reconstruction algorithm, MAGIC can be operated as a particle detector, in the sense that it can discriminate cosmic particles: protons, electrons, etc. This is the topic of sect. **2**. Finally, MAGIC has the characteristics to be sensitive to some New Physics scenarios, including dark matter and Lorentz Invariance violation, but also (if existing) to electromagnetic counterparts of gravitational wave events. These will be discussed in sects. **3** and **4**, respectively.

Due to space limitation, this contribution will be a brief overview. More detailed reports on MAGIC physics and the success of IACTA can be found for example in [2,3].

1. – MAGIC as a TeV gamma-ray detector

The presence of VHE (Very High Energy: $> 100\,\mathrm{GeV}$) gamma rays in astrophysical environment is always connected to parent highly accelerated cosmic ray particle (leptons and/or hadrons). Therefore gamma ray astrophysics probes cosmic ray physics. However, to be able to understand the particle and radiation fields in astrophysical environments, a large astronomical framework of knowledge is required, formed by a wide multi-wavelength and multi-instrument contribution. Classical targets for VHE gamma-ray observations were mentioned in the abstract. It is impossible to summarize the many results achieved with observation at VHE in the past decade. Only a selection will be discussed, in which MAGIC has shown unique capabilities.

The low MAGIC energy threshold (50 GeV), had allowed to search for the farthest sources in the sky, because of the opaqueness of the Universe to VHE gamma rays lost due to pair production with the UV-IR background radiation fields of the Extragalactic Background Light (EBL), the second radiation field permeating the universe after the

Cosmic Microwave Background (CMB). MAGIC has recently expanded the TeV universe by doubling the distance of the farthest sources known. Two sources at redshift $z \sim 1$ were detected [4, 5]: the galaxy PKS 1441+25 at $z = 0.939$ and the galaxy B0218+35 at $z = 0.944$ of which MAGIC did not observe the direct light, but that gravitationally lensed from an intervening spiral galaxy in between. This was the first gravitational-lensed delayed VHE signal ever observed.

The importance of multi-wavelengths campaign has become utter, and indeed MAGIC has developed several monitoring campaigns and Time of Opportunity programs based on external triggers. For example, during the Mrk421 campaign reported in [6], the source had the coverage of Swift-UVOT, Swift-XRT, NuSTAR, *Fermi* LAT, MAGIC, and VERITAS. The flare event not only generated an increased flux, but also shifted the emission peak toward higher energies. In the Synchroton Self-Compton scenarios, this may hint to a different (than baseline) electron population that was swept-up or one single electron population that was boosted for some mechanism. The energy-dependent variability provided an important part of the puzzle of the global picture of the target dynamics. The flares in Active Galactic Nuclei (AGNs) provide useful insights into the associated Black Hole (BH) physics. All kinds of AGNs in MAGIC catalog have shown extremely fast variability. In 2014, MAGIC saw an impressive flare of the radio-galaxy IC 310. The flux doubled in 4.8 minutes, from an object located at 78 Mpc. It is very unclear what mechanisms could provide such boost because rise-time constraints emission size: the emission region must have a size smaller than the 20%of the BH size. The proposed explanation is that particle acceleration occurs by the electric field across a magnetospheric gap at the base of the radio jet, much alike the pulsar radiation mechanism [7].

Galaxy clusters are expected to show a diffuse gamma-ray emission due to the interaction of accelerated CR with the ambient intracluster medium. Perseus (78 Mpc far) is a cool-core clusters, the brightest in X-ray and thus an optimal lab to search for gamma rays associated to accelerated particle fields in the core. The explanation for the origin of radio halos is in fact challenging and TeV gamma-ray are an unique probe. TeV gamma rays are expected in hadronic model because radio-emitting electrons are secondaries produced by CR protons interacting with the protons of the ICM, or in re-acceleration model where seed population of CR electrons are re-accelerated by interacting turbulent waves. MAGIC observed for 250 h (selected) in 4 years, providing several (model-dependent) constraints. With MAGIC data, we constrained the fraction of the energy dissipated in structure formation shocks that goes into particle acceleration to be not larger than 37%. We limited the cosmic-ray to thermal-pressure ratios to values between 2 and 20%. We constrained the magnetic fields that produce the observed synchrotron emission from secondary electrons to be smaller than $10\,\mu$G [8].

Other recent MAGIC results are available here: `https://magic.mpp.mpg.de/backend/results/latest`.

2. – MAGIC as a TeV particle detector

Besides cosmic gamma rays, atmospheric showers are initiated by cosmic rays. Actually, the number of showers generated by the latter class is more than a factor of thousand larger than those initiated by gamma rays. The ability of IACTA to discriminate between gamma and particles, and among particles, stems mostly from the different imprint in the camera produced by different primaries. MAGIC is routinely used as a particle detector. It can perform all-electron searches [9, 10], but in principle can also discriminate the charge of the particle by using the shadow of the Moon [11]. MAGIC also follows up triggers from High Energy events from the IceCube neutrino detector [12].

In the following, we focus on the preliminary results MAGIC achieved on the capability to discriminate cosmic tau-neutrinos events in the data, thus opening the possibility of MAGIC as a neutrino detector. This challenging method is based on the fact that MAGIC, from its mountain location, has a "window of visibility" of 80×5 deg^2 in the direction of the Atlantic Ocean, at zenith angles slightly below 90°. The Ocean is about 170 km away. By pointing the telescope in this window, MAGIC could detect atmospheric shower generated by tau-leptons emerging from the ocean's surface, and soon-after decaying and generating particle showers. In turn, this very energetic tau-lepton (the accessible energy range is beyond the PeV), must have been produced not too deep inside the ocean by the conversion of a very energetic cosmic tau-neutrino entering the Earth in the same MAGIC observing direction. The technique is discussed in [13] (and references therein). Tau-induced showers are discriminated because they are created much closer to the telescope compared to any other possible source of background [14]. Although the sensitivity to these signals is in principle rather high for MAGIC, at the level of even above that of IceCube above the PeV range, the prospects for actual detection of cosmic tau-neutrinos are still thin, due to very low expected flux. This may not be the case in the occurrence of a strong flare (of an AGN, or a gamma ray bursts, or from a gravitational wave event) where hadrons are expected to be strongly accelerated, thus providing also an ample neutrino flux. In this case, if the source passed through the "ocean window", the neutrino flux can be indirectly observed. This observation mode is still under development in MAGIC. However, even null observation from a flaring source could provide interesting upper limits on the amount of tau-neutrino produced locally, competitive to other instruments in the field.

3. – MAGIC as a New Physics detector

There are many theoretical arguments indicating that there may be new Physics around the TeV scale. IACTA could be valuable probes for Lorenz Invariance Violations, by observing the time-of-flight delays of photons at difference energy, a tiny effect possibly amplified by the cosmological distances at hand [15]; IACTA can probe Axion-like Particles (ALPs), that may explain the otherwise awkward observation of TeV photons from targets where we expect photons should be hardly observable, because of absorbing medium either located at the source (*e.g.* dense gas fields) or in the path to the source. By converting to ALP, faraway TeV photons could thus travel larger distances than expected. IACTA can see gamma-ray flashes from fast evaporating Black Holes generated in the early Universe and evaporating in these times; finally, the passage of exotic objects like magnetic monopoles or quark nuggets, could also generate Cherenkov light observable with MAGIC (see recent review [16]).

However, large attention is paid to IACTA for their capability as dark matter (DM) detectors. They are indeed valuable DM probes, for the following reasons: a) it is often the case that gamma rays are found in prompt annihilation or decay reaction in DM rich environment, b) the associated gamma ray spectrum, for many DM scenarios, can peak at the TeV and may present peculiar features that can easily differentiate it from a purely astrophysical one, c) DM spectra would be universal, so several different targets may be observed with exactly the same spectra, d) the shape of the spectra and its cutoff at the DM mass provide also clues for identification of DM besides detection. DM searches are done with MAGIC at several targets (see a recent review [17]). The cleanest targets in the sky are the dwarf galaxies gravitationally bound to the Milky Way and orbiting its the DM halo. These are small galaxies, with almost no stellar activity, where DM must have accreted in large concentrations (mass-to-light ratios thousands of times that of the Sun), as seen by stellar velocity dispersion. MAGIC has a large track in observing these objects. The recent large campaign (160 h) on the Segue 1 satellite galaxies provided the strongest constraints from this class of targets above few hundreds of GeV, and received the attention of the Particle Data Group [18].

4. – MAGIC as a GW counterpart detector

Gravitational waves (GWs) associated physics has recently gained a strong interest due to multiple detections of GWs by the Ligo Virgo Collaboration (LVC). Although the theoretical mapping is far from being complete, it is believed that if the merger event happen between at least one compact object (NS-NS or NS-BH mergers), a measurable gamma-ray counterpart may be expected, although its spectral energy distribution is unclear. MAGIC can rapidly reposition (< 20 sec) after receiving a GW alert from LVC. However, its small field of view (about 10 square degrees) cannot sample but a small fraction of the LVC region of interest. Despite so, MAGIC has performed follow-ups of GW161226 [19] and is refining its strategies toward a better selection of pointings.

5. – Conclusions

Although not the mainstream science, among the MAGIC science goals is that of trying to add a piece in the puzzle of cosmic ray fluxes at Earth, hunting elusive tau-neutrinos, finding signatures of New Physics. The astrophysical results are disparate, and from tens of of targets and target classes. Result are now contributing to astrophysics in a wide multi-instruments and multi-wavelengths scenarios, placing gamma-ray astrophysics into the realm of a true astronomical field. MAGIC has contributed in many ways to this success along the past 12 years. Few years ahead will be productive until the times come for the future generation of instruments in this field, with the Cherenkov Telescope Array observatory [20] already in construction close to MAGIC at the island of La Palma.

REFERENCES

[1] MAGIC Collaborations, *Astropart. Phys.*, **72** (2016) 76.
[2] Lorenz E. and Wagner R., *Eur. Phys. J. H*, **37** (2012) 459.
[3] Aharonian F. *et al.*, *Rep. Prog. Phys.*, **71** (2008) 096901.
[4] MAGIC and Fermi LAT Collaborations, *Astrophys. J.*, **815** (2015) L23.
[5] MAGIC Collaboration, *Astron. Astrophys.*, **595** (2016) A98.
[6] VERITAS, MAGIC Collaborations and NuSTAR, *Astrophys. J.*, **819** (2016) 156.
[7] MAGIC Collaboration, *Science*, **346** (2014) 1080.
[8] MAGIC Collaboration, *Astron. Astrophys.*, **589** (2016) A33.
[9] Borla Tridon D. *et al.*, in *Proceedings ICRC 2011*.
[10] Mallot K. *et al.*, *TeVPa Conference, Tokyo* (2015).
[11] Colin P. *et al.*, *Proc. ICRC* (2011).
[12] IceCube, MAGIC and VERITAS Collaborations, *JINST*, **11** (2016) P11009.
[13] Gora D. and Bernardini E., *Astropart. Phys.*, **82** (2016) 77.
[14] Gora D. *et al.*, *AIP Conf. Proc.*, **1792** (2017) 060008.
[15] MAGIC Collaborations *et al.*, *Phys. Lett. B*, **668** (2008) 253.
[16] Doro M., *EPJ Web of Conferences*, **136** (2017) 01003.

[17] Doro M., in *Proceedings of the 25th European Cosmic Ray Symposium (ECRS 2016), 4–9 September 2016, Turin, Italy*, CNUM: C16-09-04.3.
[18] Particle Data Group (Patrignani C. *et al.*), *Chin. Phys. C*, **40** (2016) 100001.
[19] MAGIC Collaboration, GCN #18776.
[20] CTA Consortium, *Exp. Astron.*, **32** (2011) 193.