EPJ Web of Conferences **319**, 01004 (2025) https://doi.org/10.1051/epjconf/202531901004
RICAP-24

Selected Studies of Celestial Gamma-ray Sources with MAGIC

Razmik Mirzoyan

On Behalf of the MAGIC Collaboration
Max-Planck-Institute for Physics (Werner-Heisenberg Institute), Garching, Germany

Abstract. MAGIC is a ground-based Imaging Atmospheric Cherenkov Telescope (IACT) for studying the sky in gamma rays in the very high energy gamma-ray domain. It pioneered measurements with IACTs down to ~20 GeV regime. MAGIC consists of double telescopes with a diameter of 17 m, separated by a distance of 85 m, operating in coincidence mode (stereo). The telescopes are located at an altitude of 2200 m above sea level in the European Northern Observatory El Roque de los Muchachos on the Canary Island of La Palma. In recent years, the MAGIC collaboration has developed innovative techniques that increased the dynamic range and sensitivity of the telescopes also at the higher energy range at about 100 TeV. In this report we want to focus on some selected observations of gamma ray sources of galactic and extragalactic origin.

1 Gamma-ray astronomy, the beginning

For a detailed historical development of the ground-based gamma-ray astronomy the reader is recommended to see the papers [1-5] and the references therein. In this short paper we want to refer to the main the developments, which have shaped todays discipline. The paper by Galbraight and Jelley from 1953 demonstrated existence of Cherenkov light pulses from the night sky produced by extended air showers. For this purpose, they used a small mirror of 25cm diameter with a 2-inch photo multiplier (PMT) in its focus. These were installed inside a light-tight bucket (a garbage bin in fact) and directed to the sky [6]. These pulses were predicted already in1948 in a study of the brightness of the night sky by P. Blackett.

1.1 Important stages in the development of ground-based gamma-ray astronomy

1.1.1 First generation telescopes

In 1958 P. Morrison and independently Cocconi suggested to perform gamma-ray astronomy. The latter predicted that having a simple cosmic ray detector of a threshold of ~1 TeV one should be able to measure a gamma ray signal from the Crab Nebula at a signal to noise ratio of 1000:1 [7]. Soon researchers built enlarged and somewhat modified versions of the original setup of Galbraith and Jelley. The largest of that type detector was built and operated by the group led by A. Chudakov. This consisted of 12 parabolic searchlight mirrors of 1.5m diameter, split into rigidly connected four groups, which were put into a fast coincidence. The experiment run at the seashore in Crimea from 1959 to 1964. No detection has been reported [8]. I estimated that for measuring a significant signal from the Crab Nebula they should have measured the source for over a few thousand hours, which obviously was not a reasonable consideration at the time. In the following years more of this type detectors, but of smaller size, were built and operated, some with ingenious features, but all of them could not measure any significant signal from any source.

An important exception was the 10m diameter Whipple telescope in Arizona on mount Hopkins. It had a tessellated mirror of F/1 optics. G. Fasio and colleagues published a 3.1 sigma signal from the Crab Nebula in 1971 with this telescope [9].

Distributed arrays of the first-generation telescopes were built and operated but again no signal could have been measured.

1.1.2 Second generation telescopes

The second-generation telescopes were based on the image recognition technique. The first such telescope was the mentioned above 10m Whipple telescope, operating a 37-pixel imaging camera in the focus. Despite the narrow field of view of 3.5° and relatively coarse resolution of a pixel of 0.5°, they managed to measure 9 sigma signal from the Crab Nebula in 1989 [10]. This detection marked the birthday of ground-based very high energy gamma-ray astronomy.

The hybrid HEGRA instrument was built on the Canary island of La Palma in 1990. It included an array of six imaging air Cherenkov telescopes, which were based on the original design of the first imaging Cherenkov telescope built at Nor Amberd cosmic-ray station on mount Aragats in Armenia, see details in [5]. The first HEGRA telescope was installed in La Palma in 1992 and after a commissioning period of about two months it confirmed the gamma-ray signal measured by the Whipple team from the Crab Nebula. Other second-generation telescopes were built by the Japanese-Australian CANGAROO and French CAT telescope collaborations. Later on, more of these types of telescopes were built; the details can be found in [5].

These telescopes succeeded to measure about 10 gamma-ray sources in the sky.

1.1.3 Third generation telescopes

The third-generation telescopes inherited the main features of the second-generation telescopes. These were built as distributed arrays of larger size telescopes. These features enabled better angular and energy resolution, improved background suppression, and thus higher sensitivity. VERITAS (4 telescopes of 12m size at ~100m inter-telescope distance), H.E.S.S. (4 telescopes of 12m size, similar to VERITAS, plus a 24mx28m large telescope in the centre of the array) and MAGIC (2 telescopes of 17m diameter, at 85m distance) began operations in the early 2000's, and discovered about 200 gamma-ray sources of different types (SNR, pulsars, X-ray binary, Black-Holes, GRBs,…) [5]. Today, these telescopes are in operation and continue the successful search for cosmic gamma-ray sources.

1.1.4 Fourth generation telescopes

The Cherenkov Telescope Array (CTA) collaboration together with the Cherenkov Telescope Observatory (CTAO) has started construction of the fourth generation of telescopes. Compared to the third generation, this joint project of about 1500 astrophysicists working in ~130 different institutions worldwide plan to build large number of telescopes of 23 m, 12 m and 4 m diameters in the northern and southern hemispheres. The new telescopes have a slightly improved optical design (a larger F/D ratio), they use novel and improved light sensors, better mirrors, employ a larger field of view and improved safety features. Detailed information on the numerous developments can be found on the experiment's website [11]. Figure 1 shows a photograph of the operational first prototype of CTA's 23 m diameter Large Sized Telescope (LST) array in the Northern Hemisphere at the Roque de los Muchachos Observatory on the Canary Island of La Palma together with the two MAGIC telescopes.

Figure 1. The IACT telescopes at the Roque de los Muchachos Observatory, left to right: MAGIC-2, LST1 and MAGIC-1. One can see that the telescopes are above the cloud cover over the Atlantic ocean. In the middle of the picture one can see the experimental building, where the dome above the roof houses the micro-LIDAR instrument. The latter regularly measures the transparency of the atmosphere.

2 The MAGIC telescope project – pioneering the sub-100 GeV observations

The MAGIC project consists of twin 17m diameter IACTs. This is a pioneering project with the concept and original aim to extend the IACT technique to energies well below the 200-300 GeV (achieved from mid-1990’s to first decade of 2000’s), down to the 20 GeV energy regime. A number of innovative techniques and technologies were necessary to develop for achieving the aimed for very low energy operation. The main issue was defined to provide a very fast opto-electronic response of the telescope. For the fast-optical response, we chose a parabolic shape for the reflector. Tessellated mirrors of 11 groups in radius of curvature between (34.0 - 36,7) m were produced to smoothly fit the parabolic shape of the reflector. This provided, for example, ~140 ps time response for delta-function like light pulses within the central 1-degree radius of the camera. Special fast photo multiplier tubes (PMT) of six dynodes and hemispherical input window shape were developed at first by the company Electron Tubes, England and later on by the company Hamamatsu in Japan. The PMT signals were converted into optical ones at ~ 850nm by modulating in amplitude the output light of the VCSEL (vertical cavity surface emitting laser) diodes, coupled to multimode optical fibres of (50/125µm) diameter. The 162 m long fibres transmitted the fast-optical signals without any degradation of time features to the experimental room, where they got converted back into electrical signals by using 300 µm size PIN diodes, coupled to optical fibres. The fast signal had a FWHM (full width at half maximum) of 2.1 ns. These were digitised by 2 GigaSample/s fast DRS4 (digital ring sampler) chips and read out. All these measures helped to reduce the signal charge integration window down to ~3 ns and thus reduced the chance probability for fluctuations of the LoNS (light of the night sky) to produce spurious triggers. Other technologies, as the light-weight structure of the carbon-fibre reflector frame in combination with AMC (active mirror control) system were used for providing a low momentum of inertia for fast and easy reorientation of the telescope. These were necessary for the fast reaction of the telescope to alerts on transient events from satellite missions like, for example, GRBs (gamma-ray bursts). The project consists of twin almost identical telescopes of 17 m diameter (~240 m^2 mirror area) and of F/1 optics, with 1039 PMT-based pixel imaging cameras in their foci. The distance between the telescopes is 86m and location height is 2200m a.s.l. on the Canary island of La Palma, at the "Roque de los Muchachos" European North Observatory. The standard coincidence trigger rate of the telescope is ~300 Hz and it is about 600 Hz when operated under the "Sum-Trigger" mode, providing a lower threshold of ~20 GeV [12].

Below we will dwell on a few selected results of the MAGIC telescope project.

2.1 IceCube 290 TeV neutrino and the flaring blazar TXS-0506+056

A high-energy neutrino-induced muon track was detected by the IceCube detector on 22nd of September 2017. It automatically generated an alert that was distributed worldwide within 1 min of the detection and prompted follow-up searches by telescopes over a broad range of wavelengths. On September 28th, the Fermi Large Area Telescope (LAT) Collaboration reported that the direction of the neutrino was compatible with a catalogued, flaring in the GeV range γ-ray blazar TXS-0506+056. The location of this source at a red-shift of 0.34 deviated only by 0.1° from the measured neutrino direction. Follow-up observations by the MAGIC IACT, revealed a γ-ray flux extending up to 400 GeV. Measurements of the source have also been carried out at X-ray, optical, and radio wavelengths. The correlation of the neutrino with the flare of TXS 0506+056 was estimated to be at the 3-sigma level [13]. These long-anticipated detections of a neutrino and gamma-rays from the same object is considered to be the first neutrino - gamma-ray multi-messenger event. This joint detection produced an avalanche of interesting studies on how a blazar can emit both neutrinos and gamma-rays.

2.2 Geminga P2 detection above 15 GeV with 6.3 sigma

MAGIC detected pulsed gamma-ray emission from the Geminga pulsar (PSR J0633+1746) between 15 GeV and 75 GeV. This was the first time a middle-aged pulsar has been detected up to these energies. Observations with MAGIC were carried out with between 2017 and 2019 using the low-energy threshold Sum-Trigger-II system. After quality selection cuts, ~80 h of observational data was used in the analysis. From the two pulses per rotation seen by Fermi-LAT al lower energies, only the second one, P2, is detected in the MAGIC energy range ≥ 15 GeV, with a significance of 6.3σ. The spectrum measured by MAGIC is well-represented by a simple power law of spectral index $\Gamma = 5.62 \pm 0.54$, which smoothly extends the Fermi-LAT spectrum. A joint fit to MAGIC and Fermi-LAT data rules out the existence of a sub-exponential cut-off in the combined energy range at the 3.6σ significance level [14].

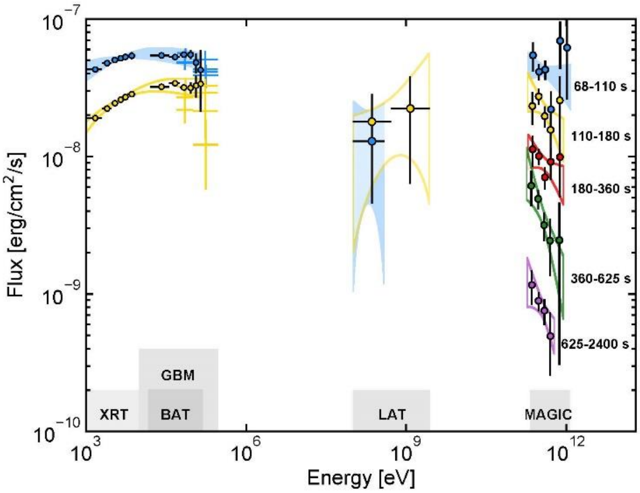

Fig. 2. The enormous intensity of GRB 190114C allowed us to follow its spectral evolution in unusually short time intervals of 42 s, 70 s and 180 s. The synchrotron self-Compton process with two-bump structure can successfully explain the TeV emission. It turns out that GRBs are even more powerful than previously thought.

2.3 MAGIC unveiling GRBs at TeV energies - GRB 190114C detection and MWL studies, GRB 201216C at red shift 1.1

For the first time MAGIC reported observation of teraelectronvolt emission from a γ-ray burst (GRB) on the night of January 14th to 15th 2019. γ-rays from the GRB 190114C were observed at about 60 standard deviations in the first 20 minutes in the energy range 0.2–1 TeV from 58 seconds after onset of the burst. We discovered a TeV emission component of the afterglow with power comparable to that of the synchrotron component. The observed similarity in the radiated power and temporal behaviour of the TeV and X-ray bands pointed to inverse Compton up-scattering as the possible mechanism of the TeV emission. Processes such as synchrotron emission by ultrahigh-energy protons were ruled out because of low radiative efficiency [15]. Two dozen satellite-born and ground-based telescopes joined the observations of the GRB190114C, covering the energy range from 5 μeV to 10^{12} eV. We found that the spectral energy distribution showed double-peak structure, with the TeV emission peaking at highest energies. The gigantic explosion of GRB 190114C allowed us to follow evolution of its spectrum in unusually short time intervals of 42 s, 70 s and 180 s, see Fig.2. This new TeV component is associated with the afterglow and can be satisfactorily explained by inverse Compton up-scattering of synchrotron photons by high-energy electrons [16]. We find that the conditions required to account for the observed TeV component are typical for GRBs, supporting the possibility that inverse Compton emission is commonly produced in GRBs. These results are considered as a big step towards a deeper understanding of the physics of GRBs and relativistic shock waves.

MAGIC detected the long GRB 201216C located at z = 1.1, the farthest source detected at very high energies. The emission above 70 GeV of GRB 201216C is modelled together with multiwavelength data within a synchrotron and synchrotron self-Compton (SSC) scenario [17]. We find that SSC can explain the broad-band data well from the optical to the very-high-energy band. For the late-time radio data, a different component is needed to account for the observed emission.

2.4 Outburst of RS Ophiuchi in 2021

Classical novae are cataclysmic binary systems in which the matter of a companion star gets accreted on a white dwarf. Accumulation of hydrogen in a layer eventually causes a thermonuclear explosion on the surface of the white dwarf, which brightens to $\sim 10^5$ solar luminosities. This triggers ejection of the accumulated matter. Novae provide the extreme conditions required to accelerate particles, electrons and/or protons, to high energies. MAGIC telescopes detected in 2021 an outburst of RS Ophiuchi, a recurrent nova with a red giant companion. We could accurately characterize its emission in the (60 – 250) GeV energy range. The combined Fermi LAT and MAGIC data suggests that preferably protons are accelerated to hundreds of GeV in the shock of the nova [18]. Such protons could create bubbles of enhanced cosmic ray density of the size of 10 pc.

2.5 Dark Matter searches

Line-like features in TeV γ rays could be seen as a “smoking gun” for dark matter and possibly new phenomena. Searching for the Galactic Centre region – possibly a dense dark matter reservoir - with an IACT for TeV spectral features is very attractive because of its superior sensitivity over any other type detector. MAGIC reported on 223 hours of observations of the Galactic Centre region at γ-ray energies up to 100 TeV. The collaboration improved the sensitivity to spectral lines at high energies using large-zenith angle observations and a novel background modelling method within a maximum-likelihood analysis in the energy domain. No line-like spectral feature was found in the analysis. This allowed to strongly constrain the cross section for dark matter annihilation into two photons at 100 TeV, achieving the best limits to date for a dark matter mass above 20 TeV for a cuspy dark matter profile at the Galactic Centre [19].

2.6 HAWC, LHAASO

Unlike IACTs, which measure Cherenkov light emission in the atmosphere, the HAWC and LHAASO detectors measure the elementary particles from air showers. In HAWC these particles penetrate the closely-packed array of 300 large water barrels, containing ~180 tons of pure water and produce Cherenkov light, which is measured by a set of four PMTs [20]. LHAASO has a similar detector, albeit of 3.3 times larger area. In addition, LHAASO has a 1.3 km² large surface array of elementary particle detectors and an underground-muon detector, which comprise ~4% of the total area. Both HAWC and LHAASO have made a number of significant detections in recent years. LHAASO demonstrated a very high sensitivity for energies ≥ 100 TeV and has discovered several tens of PeVatron sources, where particles are accelerated to PeV (10^{15} eV) energies. Recently LHAASO reported on an ultra-high energy gamma ray bubble powered by a super PeVatron [21].

2.7 Intensity Interferometry

The MAGIC telescopes are equipped with the MAGIC-SII (Stellar Intensity Interferometer) setup to explore the potential of this revived technique with the readily available IACTs. The very large size of the light-reflecting surface of IACTs, coupled with their nanosecond signal response time, make them very attractive for SII. Today, our SII setup has a real-time, deadtime-free, 4-channel GPU-based correlator. The hardware modifications allow smooth and fast switching—within seconds—between MAGIC's measurements of very high energy gamma rays and optical interferometry. We have shown that an IACT can be rendered to function as an optical intensity interferometer with relatively minor hardware modifications. Recently, we reported measurements of the diameters of 22 stars, 13 of which were made for the first time [22]. We have an extensive observing program and are improving the sensitivity of the SII configuration. The inclusion of the first prototype LST1 telescope, operating in a close proximity of MAGICs at the Northern Observatory of CTA, is currently being investigated and appears to be technically feasible. The inclusion of all IACTs of this Northern array promises a significant improvement in sensitivity that will allow us to observe fainter objects with higher angular resolution.

3 Conclusions

In October 2024 we celebrated the 20-years operation of the MAGIC project. This is one of the most successful detectors for cosmic and gamma-ray studies. It has discovered the existence of TeV gamma-rays from GRBs, was a major player in the first multi-messenger study of the neutrino and gamma rays, has discovered gamma-ray emission from the Crab and Geminga pulsars, measured the farthest sources in TeV,... The list is long. But importantly, it continues successful operation, jointly performing higher sensitivity observations with the LST1 telescope of the CTA and by including the SII observations, diversifying its scientific reach.

References

1. D. Fegan, Cherenkov Reflections: Gamma-Ray Imaging and the Evolution of TeV Astronomy (World Scientific, Singapore, 2019)
2. A.M. Hillas, Astrop. Phys. 43, 19 (2013)
3. T.C. Weekes, Very High Energy Gamma-Ray Astronomy, Series in Astronomy and Astrophysics (CRC Press, 2003) ISBN-10: 0750306580
4. A. Watson, The discovery of Cherenkov radiation and its use in the detection of extensive air showers. Nucl. Phys. B 212–213, 13 (2011).; also at arXiv:1101.4535
5. R. Mirzoyan, The Development of Ground-Based Gamma-Ray Astronomy: A Historical Overview of the Pioneering Experiments, © Springer Nature Singapore Pte

Ltd. 2023, C. Bambi, A. Santangelo (eds.), Handbook of X-ray and Gamma-ray Astrophysics, https://doi.org/10.1007/978-981-16-4544-0_62-1

6. W. Galbraith, J.V. Jelley, Nature 171, 349 (1953)
7. G. Cocconi, Proc. Int. Cos. Ray Conf. Moscow 2, 309 (1960)
8. A.E. Chudakov, V.L. Dadykin, V.I. Zatsepin, N.M. Nesterova, Soviet Trudi FIAN Acad. Sci. XXVI, 118–141 (1964); Transl. Consultants Bureau, P.N. Lebedev Phys. Inst. 26, 99 (1965)
9. G.G. Fasio, H.F. Helmken, M. O’Mongain, T.C. Weekes, Detection of High-Energy Gamma-Rays from the Crab Nebula, ApJ, 175: L117 – L122, (1972)
10. T.C. Weekes, M.F. Cawley, D.J. Fegan, et al., Astrophys. J. 342, 379 (1989)
11. CTA-Webpage: https://www.cta-observatory.org/
12. R. Mirzoyan, Technological novelties of ground-based very high energy gamma-ray astrophysics with the imaging atmospheric Cherenkov telescopes. Universe 8(4), 219 (2022). ⊲https://doi.900 org/10.3390/universe8040219
13. M. G. Aartsen, R. Abbasi, Y. Abdou, et. al., Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A, Science, **361**, 6398 (2018) DOI: 10.1126/science.aat1378
14. V.A. Acciari, S. Ansoldi, L.A. Antonelli, A. Arbet Engels, K. Asano, et al., Detection of the Geminga pulsar with MAGIC hints at a power-law tail emission beyond 15 GeV. A&A **643**, 782 L14 (2020)
15. V.A. Acciari, S. Ansoldi, L.A. Antonelli, et al., Teraelectronvolt emission from the γ-ray burst GRB 190114C. Nature **575**, 455–458 (2019)
16. MAGIC Collaboration, Observation of inverse Compton emission from a long γ-ray burst. Nature **575**, 459–463 (2019)
17. H. Abe, S. Abe, Acciari, et al., MAGIC detection of GRB 201216C at z = 1.1, MNRAS **527**, 5856–5867 (2024)
18. V.A. Acciari, A. Ansoldi, L.A. Antonelli, et al., Proton acceleration in thermonuclear nova explosions revealed by gamma rays, Nat. Astron. **6**, 689-697, (2022)
19. H. Abe, S. Abe, V. A. Acciari, et al., Search for Gamma-Ray Spectral Lines from Dark Matter Annihilation up to 100 TeV toward the Galactic Center with MAGIC, Phys. Rev. Lett. **130**, 061002 (2023)
20. HAWC Collaboration: A.U. Abeysekara et al., The High-Altitude Water Cherenkov (HAWC) Observatory in México: The Primary Detector, NIM A**1052** (2023), 168253.
21. LHAASO Collaboration, Science Bulletin **69**, Issue 4 (2024), pp 449-457
22. S. Abe, J. Abhir, V. A. Acciari, et al., Performance and first measurements of the MAGIC Stellar Intensity Interferometer, MNRAS 529, 4387–4404 (2024) https://doi.org/10.1093/mnras/stae697