THE MAGIC OF ACCELERATION*

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MAGIC is an array of two 17-m diameter Cherenkov telescopes observing gamma rays in the very-high-energy (VHE; above a few tens of GeV) range. MAGIC has been in operation since 2003, leading a successful observational program covering a broad range of scientific topics. Observations of gamma-ray emission from Galactic or extragalactic sources allow us to probe the conditions of acceleration of charged particles in them. We will report on the recent highlight results of MAGIC, shedding light on acceleration and radiative cooling processes in cosmic sources. In particular, we will discuss the recently added new member of the VHE Flat Spectrum Radio Quasar family: B2 1420+32 during its 2020 flaring state, the steepest source detected in VHE gamma rays: the Geminga pulsar, and the newly discovered at VHE gamma-rays nova RS Ophiuchi.

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1. Introduction

MAGIC (Major Atmospheric Gamma Imaging Cherenkov) [1] is a system of two Imaging Atmospheric Cherenkov Telescopes (IACTs). They are located in Observatorio Roque de los Muchachos (28.7° N, 17.9° W), on the island of La Palma, Spain, at the height of 2200 m a.s.l. Its main target are the observations of gamma-ray radiation from cosmic sources in the very-high-energy ($\gtrsim$ a few tens of GeV) range.

MAGIC's large mirror diameter of 17 m allows an energy threshold as low as ~ 50 GeV for a standard trigger [2] and ~ 20 GeV for a dedicated SUM-Trigger-II [3]. Strong background rejection due to stereoscopic observations results in the integral sensitivity of $1.45 \pm 0.02\%$ of Crab Nebula flux in 50 hours of observations above 104 GeV [2]. Excellent performance at the

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lowest energies is critical in the case of observations of sources that are either intrinsically soft (such as pulsars) or have their higher energy part absorbed on the way to the observer (such as distant active galaxies or gamma-ray bursts).

The MAGIC data are analyzed using the standard analysis package MARS (MAGIC Analysis and Reconstruction Software) [2, 4]. The raw data are calibrated, images of individual events are cleaned to lower the influence of the night sky background, and parametrized as Hillas ellipses [5], including a set of additional image parameters (*e.g.* connected with the arrival times of the signals in individual pixels, or possible clipping of the image at the edge of the camera). The events from both telescopes are matched, and further reconstruction of the individual showers proceeds (determination of the particle type, its energy, and arrival direction), exploiting also multivariate decision trees.

2. MAGIC observational program

The MAGIC scientific program covers a large range of various topics:

— Galactic Science: Supernova Remnants, Pulsar Wind Nebulae, Galactic Center, Pulsars, Novae.

— Extragalactic Science: mainly various types of Active Galactic Nuclei (AGN), with a focus on blazars.

— Transient and Multi-messenger: follow up of gamma-ray bursts (GRB), gravitational waves, neutrino alerts.

— Fundamental Physics and Cosmology: Dark Matter searches, studies of Lorentz Invariance Violation effects, probing Extragalactic Background Light (EBL) and Intergalactic Magnetic Fields.

The observations of gamma-ray radiation for a given source reveal the underlying high-energy processes (acceleration and interaction of relativistic particles). In most of those applications, electrons and/or protons are accelerated to ultrarelativistic energies in cosmic sources, interact with ambient radiation fields or with matter, producing gamma-ray emission that can be observed on Earth and attributed to the cosmic source. By studying the details of the gamma-ray emission in the time and energy domain, we are therefore able to probe the acceleration processes occurring in those sources. In the sections below, we report on a few selected recent results obtained with the MAGIC telescopes.

2.1. GRB 190114C

Gamma-ray bursts (GRBs) are short flashes of electromagnetic radiation seen from cosmological distances (see *e.g.* [6]). They have rapid and highly variable emission component possibly connected with the acceleration of particles in the inner shocks of the GRB jet. It is then followed by a longer (days to months) afterglow phase that is related to the interactions between the jet and the surrounding medium.

For two decades, the current generation of IACTs has been trying to detect VHE gamma-ray emission from a GRB (see *e.g.* [7–9]). The GRB distance distribution peaks at $z \sim 1$, making MAGIC an ideal VHE instrument with its excellent low-energy performance, to counteract the EBL absorption. Moreover, the detection of these transient events, decaying fast after minutes from the burst, requires a combination of rapid repointing and, ideally, favorable observational conditions (low zenith distance angle, no Moon light).

GRB 190114C, at $z = 0.424$, is a long GRB with $T_{90} = 361\,\mathrm{s}$. It was the first GRB from which VHE gamma-ray radiation has been claimed [10]. Due to the rapid repositioning of the MAGIC telescopes, the observations started already 50 seconds after the *Swift*-BAT trigger. In the first seconds of the observations, the source was the brightest ever gamma-ray emitter, reaching the level of 100 times exceeding that of Crab Nebula. It is remarkable that due to the high flux of the GRB, it could be measured up to energies where EBL absorption lowers the observed flux by three orders of magnitude. The emission has been measured up to the TeV range, an order of magnitude above the expected synchrotron cut-off [10]. This for the first time clearly shows what was already suspected — that the VHE gamma rays from GRB are not simply an extension of the synchrotron radiation to higher energies, but originate in a second emission component.

The modeling of the multi-frequency data confirms indeed the need for a combination of synchrotron radiation and synchrotron-self-Compton (SSC) components [11].

2.2. FSRQ QSO B1420+326

FSRQs (Flat Spectrum Radio Quasars) are a class of blazars, AGN objects with one of its jets aligned to the line of sight. Due to their strong radiation fields originated from the accretion disk, Broad Line Region and dust torus, their modeling can be more complex than the other classes of blazars, the BL Lac objects, dominated by the emission from the jet only. While we know hundreds of FSRQ at GeV energies, (see *e.g.* [12]), so far only 9 such-classified sources were detected at VHE gamma-rays (http://tevcat.uchicago.edu/). Curiously, they show violent variability, which points to a small emission region that could be comfortably located in the inner part of the jet. However, the observations of VHE gamma rays put opposite constraints on the location of the emission region due to the strong absorption of the inner BLR radiation field.

One of the latest additions to the VHE FSRQ family is QSO B1420+326, also known as OQ 334. The source is fairly distant, with the redshift of 0.682 [13]. Like other sources of this class, QSO B1420+326 exhibits strong gamma-ray variability. In December 2019, it started a flaring activity. Follow-up of the source with the MAGIC telescopes led to its first detection at VHE gamma-ray range [14]. A long duration of the high state allowed MAGIC to gather a large dataset of multiwavelength observations, in radio, near IR, optical (including polarimetry), UV, X-ray, GeV, and VHE ranges. In addition, follow-up by optical spectroscopy and radio interferometry was performed. The radio interferometry revealed a new knot ejected from the core. Interestingly, the time of VHE gamma-ray emission is consistent with the passing of the upstream edge of the knot through the centroid of the core.

The data were divided into four periods [14], describing the pre-flare, optical flare, VHE flare, and post-flare period, and in each period, an independent MWL modeling of the emission was performed. The leptonic scenario was applied using `agnpy` code [15]. The FSRQ nature of the source makes the External Compton (EC) scenario a likely option for the VHE gamma-ray emission when the IR radiation from the dust torus is considered, located beyond the BLR absorption. Nevertheless, the source also showed an impressive increase in the optical flux, which forces us to also consider SSC emission. The daily time scale of variability limits the size of the emission region. The electron energy distribution was determined by a balance of the cooling, acceleration, and dynamic time scales, and expressed as dependent on physical units, such as the efficiency of the acceleration. Gamma rays are thus explained as the EC emission on the dust torus photons. The highly variable in shape X-ray emission instead comes as a combination of the falling edge of the synchrotron radiation, the bulk of the SSC component, and the rising edge of EC. The resulting modeling is close to the equipartition of the electron and magnetic field energy density: $u_e/u_B = 0.06$–1.6 [14].

Both the flux and the peak position of the spectral energy distribution of QSO B1420+326 shifted by over two orders of magnitude [14].

2.3. Geminga pulsar

Pulsars are rapidly rotating and strongly magnetized neutron stars, in which the cone of electromagnetic radiation is crossing the observers' line of sight, causing one or two observed pulses per period [16]. Geminga is one of the brightest pulsars seen in GeV gamma rays [17]. Hence, it was considered as one of the possible targets for searches of VHE gamma-ray emission from the pulsar. However, even a deep exposure of 63 hrs [18], turned out to be insufficient to detect such an emission due to the intrinsic steepness of the spectrum. The source was detected by the MAGIC telescopes with 80 hrs of exposure [19], when they were equipped with a dedicated low-energy trigger, the so-called SUM-Trigger-II [3].

The spectrum of Geminga at the VHE gamma-ray range is extremely soft (photon index of -5.62 ± 0.54) [19]. This, on the one hand, made it a challenging detection, on the other hand, when combined with the SumTrigger-II, the MAGIC telescopes were able to reconstruct the spectrum of Geminga down to 15 GeV. Joint MAGIC and *Fermi*-LAT fit rules out a sub-exponential cut-off of the emission at 3.6σ level, hinting a power-law tail extension at $E > 15$ GeV [19].

The gamma-ray emission is explained as stemming from $e^{\pm}$ accelerated in the outer gap scenario [20], with the flux $\lesssim 40$ GeV dominated by the curvature radiation. The $\gtrsim 40$ GeV emission is dominated by the IC scattering by inward going electrons of soft X-rays from the surface of the neutron star.

2.4. RS Ophiuchi

Novae are binary stars in which the matter of a companion star is accumulated on the surface of a White Dwarf, eventually leading to a thermonuclear runaway [21]. In the last years, novae have been shown to emit gamma-ray radiation [22, 23]. The GeV detection, as well as the possibility for a second component at VHE gamma rays [24], triggered creation of a novae follow-up project within the MAGIC Collaboration [25]. While the occurrence of gamma-ray emission clearly points to high-energy processes occurring in the novae, *Fermi*-LAT detections alone did not allow us to disentangle the two possible emission scenarios: leptonic and hadronic.

RS Ophiuchi (RS Oph) is a symbiotic recurrent nova, *i.e.* a White Dwarf close to the eruption threshold and a Red Giant companion that provides sufficient material for an eruption every ~ 15 years [26]. The latest outburst of RS Oph happened on the 8$^{\text{th}}$ of August, 2021. The follow up of this event with Cherenkov telescopes led to the first detection of a nova at VHE gamma-rays, independently by H.E.S.S. [27] and MAGIC [28].

The MAGIC observations of RS Oph allowed the reconstruction of the spectra for each of the first 4 days of the eruption, and no significant emission after 3-week break (due to a combination of bad weather and full Moon time). Despite the rapid decline of the optical and GeV fluxes, the flux level > 100 GeV was consistent with a constant over the first four days [28].

High energy particles are expected to be accelerated at the nova shocks. We considered two gamma-ray emission models. In the leptonic model, electrons produce gamma rays as a result of inverse Compton scattering of the photosphere radiation. Due to the strong radiation field and the relatively large cross section of the IC process, the electrons are rapidly cooled, thus producing an excess of radiation at sub-GeV energies. The rapid cooling is also the limiting factor of the maximum energies that electrons can achieve. In the hadronic model, protons will interact with the local matter (mostly the nova ejecta, but partially also the RG wind). Due to a much smaller cross section, they will rarely interact more than once, escaping the nova region and possibly adding up to the Galactic Cosmic Ray budget. Due to a lack of strong cooling processes, the energy of protons is expected to grow linearly with time (if the acceleration conditions stay the same).

We performed fits to the RS Oph data with both models and found a strong statistical preference for a proton model [28]. In addition, the proton model naturally explains the drop-off of the emission at sub-GeV energies, whereas the electron model predicts a bump instead. The required shape of the particle energy distribution obtained from the fit is also much more natural in the case of protons since the cooling breaks would emerge from the model itself. Finally, day-by-day modeling analysis shows a hint of increase in the maximum proton energies, that is consistent with the acceleration-time limited scenario of protons.

3. Conclusions

The MAGIC telescopes, via observations of gamma rays, allow us to probe acceleration scenarios in many different types of objects, both Galactic and extragalactic. In order to obtain a broad view of the sources, multiwavelength observations are however needed. In this contribution, a few recent cases of such interesting results have been presented. GRB 190114C, the first GRB whose detection has been claimed by IACTs, and that showed clearly that the VHE gamma-ray emission from GRBs is not a simple extension of the low-energy emission, but has a second component, likely due to inverse Compton scattering. QSO B1420+326, an FSRQ with broadband emission characterized during a major flare. Geminga pulsar, the steepest source observed by IACTs, allows us to probe processes in the vicinity of those compact objects. And finally, RS Oph, the first nova detected in VHE gamma-rays, whose detection in the VHE region by MAGIC showed us that the gamma-ray emission from novae is produced in hadronic interactions.

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