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# Very large zenith angle observations with the MAGIC telescopes

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**Summary.** — The MAGIC telescopes exploit the cosmic gamma rays impacting our atmosphere to monitor the night sky at very high energies. These particles generate electromagnetic showers, which cause the emission of Cherenkov radiation measured by MAGIC. Shower properties change when shifting from zenith to horizon, which enables the detection of the highest-energy particles. The presented research focuses on the largest zenith angle observations with the MAGIC telescopes, as well as on the technical improvements needed to optimise the data analysis. This will make it possible to understand some of the relevant systematics in such conditions, and in perspective, to enhance MAGIC sensitivity and to improve science results.

## 1. – Introduction

**1**˙1. *Limitations in high energy astrophysics*. – Since the second half of the 20th century astrophysics started investigating the non-thermal Universe by means of high energy photons.

Depending on the physical processes involving the observed radiation along the entire electromagnetic spectrum, different types of detectors have been developed.

The main reason for this technological effort is that Earth's atmosphere acts as an absorber for radiation at different wavelengths, resulting in a varying atmospheric opacity.

For parts of the spectrum —the infrared, part of the optical spectrum and over the extreme ultraviolet— it was clear that a ground-based telescope could hardly provide a sufficient signal.

With the beginning of the race for space conquest, technology allowed humankind to explore the outer space and beyond from a much rarefied and sterile environment.

Even though space-borne particle detectors are still an essential ingredient for current science —as it was first for military purposes [1]— they could not stand to the ever increasing search for extreme and atypical phenomena in astrophysics.

Over tens of GeV energy spectra are usually observed to be consistent with negative power laws, which implies a lower flux as the energy increases. In order to accumulate signal over the complicated backgrounds observed, the decrease in flux must be counteracted by an increase in the effective area of the detector. Since satellites' dimensions are necessarily limited by costs, it is evident that over a certain energy they will suffer from lower detection rates.

Already in the first half of the same century, pioneering works by Auger [2], Hess [3] and Rossi [4] set the foundations for the development of the first facilities designed to exploit Earth's atmosphere as part of the detector, thus overcoming the limitations of space-borne observatories.

**1**˙2. *Cherenkov radiation.* – The underlying physical process which allows this is the Cherenkov effect [5]. The gas which makes up the atmosphere can be modelled locally as a dielectric medium, *i.e.* it can be electrically polarised.

The strike of a particle of extraterrestrial origin, called *primary*, will eventually cause a high energy interaction with one or more of the gas particles comprising the atmosphere.

This nuclear process will trigger a chain reaction which will in turn produce an immense number of other nuclear and subnuclear particle interactions and products —called *secondaries*— spanning both leptonic and hadronic channels.

Among the great amount of particles involved, the ones that possess an electric charge are the responsible for the Cherenkov effect, which is in the end a convolution of two simultaneous factors.

The first one is related to electrodynamics: an electrically charged particle possesses an electric field interacting at every time with the ones belonging to other particles, in particular atoms and molecules such as molecular gas species in the atmosphere.

This causes the ambient electric fields to polarise, thus creating electric dipoles that at this point surround the moving charge. As for any quantum mechanical change of state, the excited system will tend to restore its equilibrium configuration, resulting in radiation emission at a wavelength that depends on the system own properties.

The second effect is related to the kinematics of the disturbing particle and to the properties of the medium in which it travels.

Special relativity states that the speed of light cannot exceed the maximum value $c$ defined in vacuum, and from quantum electrodynamics it is known that photons travelling in a medium will undergo interactions with matter. This implies that light speed will assume lower values depending on the medium in which it travels, which also defines its refractive index $n$.

If the traversing particle has enough energy such that its velocity $v_p$ satisfies the relation

$$\frac{c}{n} < v_p < c, \tag{1}$$

then the radiation emitted from the surrounding relaxing electric fields will not be able to travel more than the space covered by the energetic particle,

$$x_p = v_p t = \beta c t, \tag{2}$$

where $\beta$ is the ratio of $v_p$ to the speed of light in vacuum $c$.

The induced radiation will instead cover no more than

$$x_{rad} = \frac{c}{n} t. \tag{3}$$

The geometry of the problem restricts said radiation to be emitted within a cone of semi-aperture given by

$$\theta = \arccos\left(\frac{\frac{c}{n}t}{\beta ct}\right) = \left(\frac{1}{\beta n}\right). \tag{4}$$

It can be noted that the more energetic the traveling particle is, the narrower will be the light pool.

The frequency spectrum of Cherenkov radiation was calculated soon after its discovery: unlike other similar atomic emission processes, it does not give rise to spectral peaks but it is rather continuous.

Around the visible part of the electromagnetic spectrum the monochromatic intensity is proportional to the frequency, so most of the Cherenkov light is emitted towards the ultraviolet.

**1˙3.** *The imaging atmospheric cherenkov technique and the MAGIC telescopes.* – Since the beginning of $\gamma$-ray astronomy these have been the technological and physical arguments that justified an effort in this direction.

The link between the high energy cosmic rays and the increasingly interesting $\gamma$-ray astrophysics culminated in the Imaging Atmospheric Cherenkov Technique (IACT) [6].

There is a number of considerations to be made in order to understand how the Cherenkov effect can be used to produce science in astrophysics.

Given the high number of interactions and the relatively low energy of Cherenkov radiation, the showers will not propagate infinitely, but they will rather be subject to different diffusion processes (relevant for the IACT are Mie scattering caused mainly by dust particles and Rayleigh scattering). To equilibrate between a sufficient shower development and a low rate of absorption, an IACT facility needs to be located at a relatively high altitude (about 1–2 km).

An IACT telescope employs a set of mirrors to concentrate the Cherenkov light when the shower front hits the ground. Depending on the position of the instrument within the light pool, a certain amount of photons will reach a camera placed at the focal point, defined by the mirror configuration.

The camera is itself a multi-component instrument, in which photo-multipliers convert the received photon counts in photo-electrons. Once the light signal is converted into an electric impulse, a reconstruction analysis is issued in order to retrieve the information related to the projected image.

A fundamental part of the IACT technique is the separation between showers triggered by $\gamma$-rays (or in general leptons) and those that are instead produced through hadronic channels. Due to the different amount of scattering processes and lepto-hadronic channels —such as $\pi^0 \to 2\gamma$— hadronic showers tend to develop also perpendicular to the shower main axis. This results in a basic difference between the respective images, in which the ones generated through $\gamma$ rays are similar to the events in fig. 1, whereas cosmic rays generate usually more scattered images.

In order to exclude as much background as possible and improve the signal-to-noise ratio (SNR), images are cleaned by extracting the ellipse-shaped cluster, containing the bulk of the signal, from the overall background for each of the registered showers.

Given the degree of freedom represented by the semi-major axis of the ellipses, each projected image is affected by a degeneracy over its direction. Nowadays IACT facilities usually employ multiple telescopes in order to solve this ambiguity and to track the source

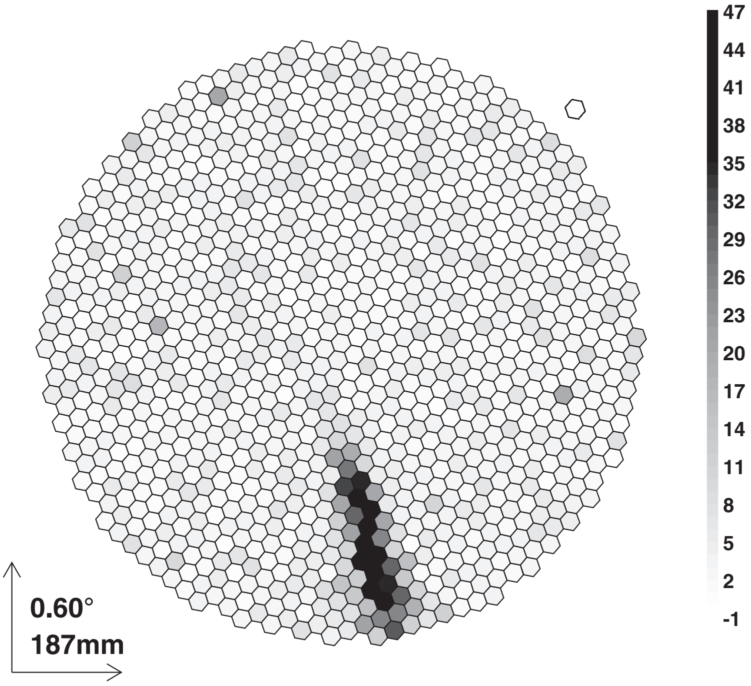

Fig. 1. – Example of a gamma-like event taken from a low zenith Monte Carlo simulation. The camera is represented here as a set of hexagonal units, each one depicting a photo-multiplier. The color scale describes the number of photo-electrons that reached a unit. The nature of a shower is reflected by the shape of the image —in this case a definite ellipse— but also by estimating its geometrical dimensions and measuring its brightness, here reflected by the darker colours.

position in the sky —projected into the camera— through the stereoscopic intersection of the associated images.

The two Major Atmospheric Gamma Imaging Cherenkov telescopes (MAGIC, `https://magic.mpp.mpg.de`) belong to this class of instruments, observing the skies over the Roque de Los Muchachos Observatory (La Palma, Canary Islands).

They began operations in 2004 and 2009 respectively, undergoing a recent major upgrade [7, 8] in order to normalise and boost their performances.

The main features of the MAGIC telescopes have been a lower energy threshold and a fast movement in order to be sensitive to energies of tens of GeV, where space-based observatories start to lose their detection rate capabilities, and to react promptly to their observational alerts.

## 2. – The case for very large zenith angles observations

Recent developments in cosmic ray (CR) physics have directed their attention to tackling the origin of the highest energy particles. In particular, recent focus has been given to the PeV regime, in order to investigate possible heterogeneous compositions in the astronomical populations responsible for their emission, an evidence recently supported by data from the Pierre Auger Collaboration [9]. This is important in order to clarify

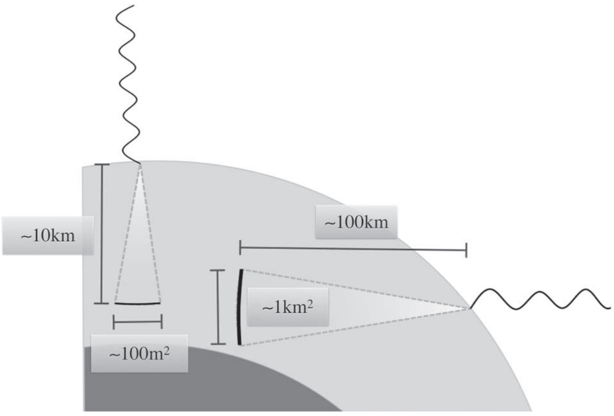

Fig. 2. – Geometrical depiction of the zenith dependence in atmospheric particle showers.

the underlying acceleration processes.

The reasons behind the rise of ground-based very high energy (VHE) $\gamma$-ray astronomy are the same that prompt today the MAGIC Collaboration to contribute to these findings in cosmic ray physics.

The convenience in using the atmosphere as a calorimeter is evident from the fact that its size is much bigger than the space-borne equivalent. Due to the steep decreasing energy spectra at VHE, the focus of very large zenith angle (VLZA) observations is to increase as much as possible the measurable flux of particles at those and higher energies.

The cheapest way to do this is to take advantage of the atmosphere's thickness profile along the zenith angle direction, namely from above the observer's position (Zenith) to the horizon. At high zenith angles the showers start to develop increasingly far from the observer. As fig. 2 shows, since the shower's development is longer, but its opening angle remains constant, the basis of the shower is wider than in the low zenith regime. This means that the Cherenkov light pool is larger and the result translates into an increase of the IACT collection area.

This concept started to be investigated early by [10] and is currently tested by the MAGIC Collaboration.

Due to its key role in shaping the particle showers and consequently the amount of signal they deposit on the mirrors, the atmosphere constitutes a mixed blessing for VLZA observations.

The boost in collection area is counteracted by the longer development of the showers, resulting in an increased absorption of Cherenkov photons at lower energies —regardless of the primary particle's nature. As fig. 3 shows, recent Monte Carlo simulations manage to display the balance between the increase of both collection area and energy threshold.

The higher probability for the Cherenkov photons to be absorbed reflects also in a lower count rate, as shown in fig. 4.

A critical aspect of the current research in VLZA angles is how much estimating these effects can effectively help in reducing the background and boosting the SNR. The MAGIC Collaboration is improving its Monte Carlo simulations, in order to progressively account for the limitations relevant in VLZA observations.

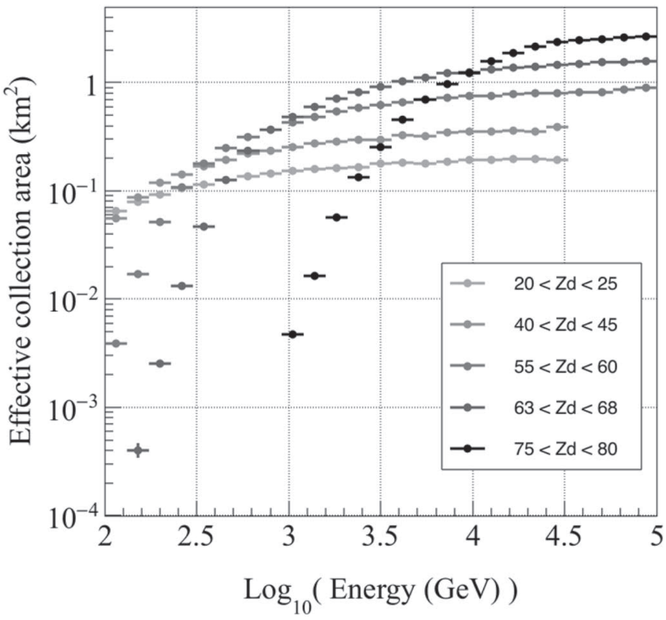

Fig. 3. – Dependence of the collection area on the zenith angle from Monte Carlo data.

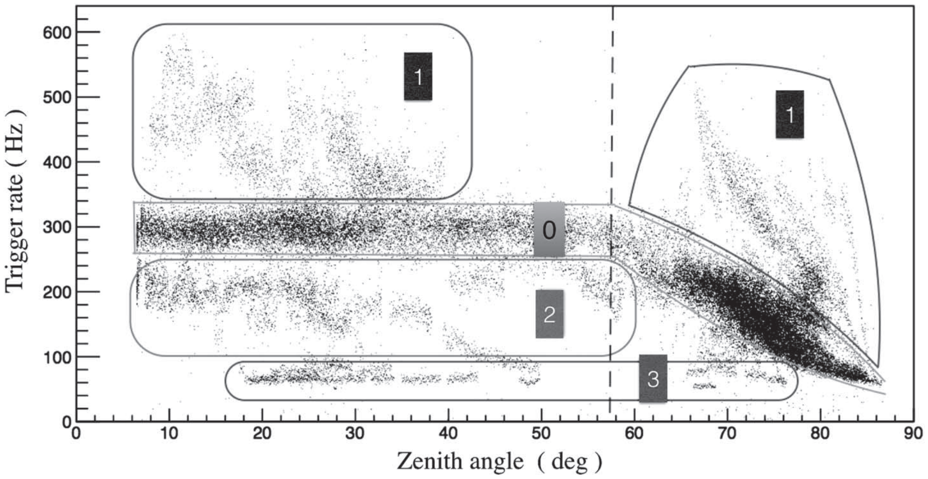

Fig. 4. – Stereoscopic trigger rate evolution with zenith angle. Observations during many days allow to recognise different populations: (0) stable, good data, and data affected by (1) diffusion, (2) absorption and (3) different levels of night sky background light. Atmospheric attenuation contributes to the non-linear decrease of the particle flux —regardless of its origin— and so of their associated trigger counts when observing progressively towards the ground.

## 3. – Technical challenges and current work

Any IACT experiment or observatory needs information about the transmission of Cherenkov light through the atmosphere, which provides the biggest contribution to systematics. These difficulties increase noticeably at very large zenith angles, because there is more volume in which clouds and dust can obstruct the showers.

During normal scheduled observations, the MAGIC telescopes are aided —when possible— by a diverse set of instruments in different wavelengths.

These instruments work as independent subsystems, taking auxiliary data coupled afterwards to the actual Cherenkov data along the analysis pipeline.

Besides the dedicated Monte Carlo simulations, this measurements are essential to assess data quality, especially when water vapour (clouds) or dust (Calima) are present.

Among these tools, the most efficient is a “micro”—Light Detection and Ranging (LIDAR) system [11], which follows the MAGIC pointing from a dedicated dome.

The purpose of such instrument is to make a differential measure of backscattered light from the atmosphere along the shooting line of sight (LOS). This measure is then translated into an estimate of the extinction of Cherenkov light due to different absorbing components within the atmosphere. During the analysis pipeline, the process culminates with the application of the relative corrections to the estimated energy of the registered events, resulting in a higher precision of flux and energy measurements.

Given the limited laser power, the instrument capabilities are not sufficient to shoot the laser at great distances, such as those qualitatively shown in fig. 2. This means that the LIDAR cannot be used effectively during VLZA observations, accounting for only about 10% of the required transmission value, a contribution too small to counteract the large-zenith effects on the showers.

An alternative which has been considered is a *pyrometer*, *i.e.* a type of thermometer which exploits thermal radiation —in particular mid-infrared emission.

This device is mounted on the side of the dish of MAGIC-1 and provides an integral measure of the sky’s temperature within 2° along the LOS. This value is then used to estimate the absorption given by the column of material within its angular aperture, based on the fact that any obstacle (*e.g.*, a cloud) will emit more thermal radiation then a path free of dense material.

However, a measurement like this is affected by two non-trivial factors, both arising from its integral nature:

- any information about the contribution of different components (dust, water vapour) to the measured value gets flushed within the data;
- the thickness of the atmosphere increases when pointing closer to the ground, so the temperature gets higher simply due to more medium along the line of sight, and not because there is a specific absorbing obstacle. An example of this is shown in fig. 5.

For these reasons the two instruments considered above are not optimal for use during VLZA observations.

To bypass these difficulties, a yet different solution has been applied. This aiding technique, borrowed from optical astronomy, is somewhat similar to the pyrometer measure, but more reliable: optical measurements of light attenuation.

At the center of MAGIC-1 is a space designed to host various subsystems, among which is placed a CCD camera able to make images of stars in the field of view (FOV) in various filter wavelengths.

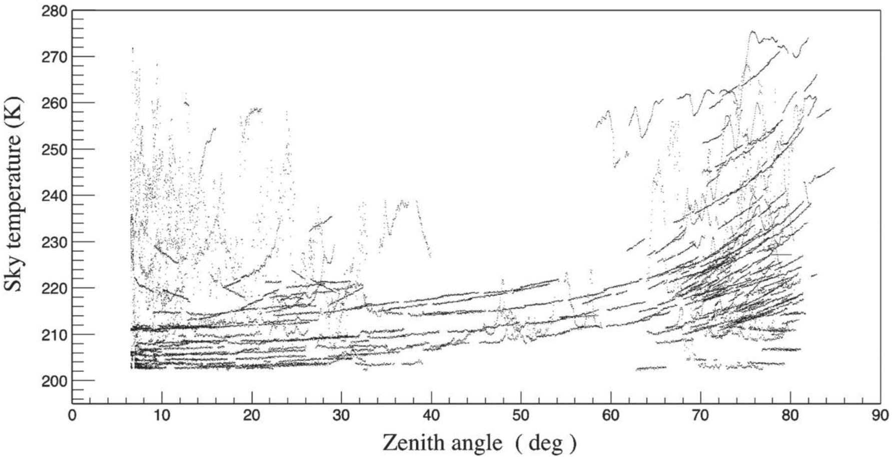

Fig. 5. – Zenith angle dependence of thermal sky temperature measured by the MAGIC pyrometer. Each curve represents a single data run. It can be seen that in some cases the sum of varying absorbing obstacles along the LOS gives rise to local fluctuations, but each run is modulated by a smooth background which increases with the zenith angle.

Assuming a star emits light which reaches the Earth with an intensity $I_0$, a telescope on the surface will observe a damped intensity $I$; the relation between these intensities with the apparent magnitude $m$ of the star is

$$m = M - 2.5\log\left(\frac{I}{I_0}\right), \tag{5}$$

where $M$ represents the star's magnitude outside the atmosphere, *i.e.* before the attenuation.

The intensity measured from the ground will of course decrease with the zenith angle ($z$), and at the same time it depends on the intrinsic properties of the medium, such as its chemical composition and regional variations.

Taking into account the density profile as a function of zenith angle and altitude $h$, $\rho = \rho(z, h)$, an optical depth $\tau$ can be defined along the LOS,

$$\tau = \int_{x_0}^{x} \alpha\rho(z, h)\mathrm{d}h, \tag{6}$$

where $x_0$ represents the altitude at the observer position, $x$ the distance at which the amount of extinction is calculated and $\alpha$ the absorption coefficient associated with the medium given by the atmosphere.

This value of the optical depth is responsible for the extinction of light intensity measured at the ground, *i.e.*

$$I = I_0 e^{-\tau}, \tag{7}$$

which can be substituted in eq. (5) and allow its rewriting in terms of the properties of the medium.

At this point the relation becomes rather empirical; usually it is provided through numerical tables that depend on the set of approximations used to model the atmosphere and estimate $\tau$.

The attenuation, or atmospheric extinction, is usually parametrised through the concept of *airmass* $X$: the path length that radiation has to travel through the atmosphere at a certain zenith degree.

Making use of these prescriptions, eq. (5) becomes a linear relation,

$$m = M - \beta X(z), \tag{8}$$

where $\beta$ is a refactored parameter which encapsulates all the underlying assumptions about the atmospheric properties. The relation can be calibrated using a set of images taken at different values of the zenith angle, which allow to compute $\beta$ and apply the corresponding correction on the estimated energy.

Nevertheless the application of optical photometry in VLZA observations could help to assess in an independent way the absorption model employed in the production of the Monte Carlo simulations.

## 4. – Conclusions

Current research in the MAGIC Collaboration involves observations at very large zenith angles.

Activities in this direction have involved deeper studies about the atmospheric effects in such conditions, and an effort in defining appropriate procedures for observations and reduction of data.

Part of the ongoing efforts revolves around the improvement of Monte Carlo simulations and the development of new techniques within the analysis chain.

The goal of this project is to improve the capabilities of the MAGIC telescopes at very large zenith angles, and, in particular, increase their sensitivity for the highest energy observations of cosmic sources.

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