Ground-Based VHE γ Ray Astronomy With Air Cherenkov Imaging Telescopes

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Abstract

The history of astronomy has been one of scientific discovery following immediately upon the introduction of new technology. In this report we will review shortly the basic development of the atmospheric air Cherenkov light detection technique, in particular of the imaging telescope technique, which in the last years led to the firm establishment of a new branch in experimental astronomy, namely to ground-based very high energy (VHE) γ ray astronomy. Milestones in the technology and in the analysis of imaging technique will be discussed. The design of the 17m ø MAGIC Telescope, being currently under construction, is based on the development of new technologies for all its major parts and sets new standards in the performance of the ground based γ detectors. MAGIC is one of the next major steps in the development of the technique being the first instrument that will allow one to carry out measurements also in the not yet investigated energy gap between $10 - 300$ GeV.

Key words: VHE gamma rays, Cherenkov telescope, gamma telescope

1 Introduction

Considering different sources of light which give contribution to the light of the night sky (LONS), in 1948 Blackett has predicted that there should be Cherenkov light emission from relativistic cosmic particles impinging into Earth's atmosphere and estimated that these should give some small ($\sim 10^{-4}$) contribution into the total intensity of LONS [1]. Confirmation of that predicition and the beginning of the atmospheric air Cherenkov technique was the discovery of Galbraith and Jelley which goes back into 1953. They have used

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a single PMT in the focus of a simple parabolic mirror of 25cm ø and counted Cherenkov light flashes from extended air showers, initiated by energetic cosmic particles, at a rate of 1/min [2].

2 Development of the technique

The progress in VHE γ astronomy can be seen from the point of view of achievements which allowed one to improve the sensitivity of the technique as well as from the point of view of extending its applicable energy range.

2.1 Key steps in improving the sensitivity

Below are outlined the key developments which provided the viability and improved the sensitivity of the technique:

- In the beginning one has used just a single PMT in the focus of a small mirror in order to build a telescope (the so-called 1st generation telescopes).
- These were followed by the increase of the instrumental scale by using larger reflectors for individual telescopes and by using more than one telescope, located either close to each other or separated by some distance, and by setting them into coincidence in time. Typically such a telescope consisted of a searchlight mirror of 1-2m ø of about 0.5° angular resolution and of a single PMT in its focus (although the reflector of the 10m ø Whipple telescope, which is so far the largest in the field, has a tessellated structure since the very beginning in 1968). These were counting rate experiments trying to measure a statistically significant difference from the so-called on-source direction and somewhat offset off-source direction in the sky where presumably there was no source. The field of view of these telescopes (in fact the size of the diaphragm set in front of the PMT) and the different intensity of LONS in on-source and off-source directions were strongly affecting their performance. One should mention that by using the above mentioned technique many measurements of sporadic signals (or perhaps also of fluctuations) were reported from a number of cosmic sources on a relatively small significance level, typically $3-4\sigma$. It was essentially this approach that was used in γ astronomy in the late 50's, in the 60's and in the 70's (incidentally, it is interesting to mention the experiment of Hill and Porter in 1961 who, by using an image intensifier in the focal plane of an 8" diameter Schmidt telescope, have obtained the first high resolution images of air showers in Cherenkov light [3]).
- The next milestone was set in the 80's by the use of a coordinate sensitive imaging camera (instead of a single PMT) in the focal plane of a large

reflector (it is interesting to note that similar cameras, known as γ cameras, were widely used in nuclear medical imaging since the 60's). Today these detectors are known under the name of atmospheric air Cherenkov imaging telescopes (also, they are called 2nd generation telescopes) and they provide the highest sensitivity to γ rays in atmospheric air Cherenkov technique.

- The breakthrough in the imaging technique came with the introduction of the second moment parameterization of images by M. Hillas [4]. He has shown that both the image shape and the orientation contribute to the efficient selection of γ images from the much more numerous hadron ones (the latter is considered as a very intense, unwanted background). In spite of originally crude pixelisation of imaging cameras (the first imaging camera of Whipple had just 37 pixels of 0.5° ø each), application of Hillas parameterization to the Whipple data provided the first highly significant (9σ) measurement of γ rays from the Crab nebula in 1988 [5]. A new era in experimental γ astronomy has been started with this measurement. High standards were established concerning source discovery. It is interesting to note that calculation of the expected flux of γ rays from the Crab nebula by the pioneer γ ray astrophysicist T.C. Weekes from Whipple has preceded his experimental discovery by 20 years [6].
- The sensitivity of imaging telescopes was further improved by the use of fine pixelised cameras of pixel sizes $0.10 - 0.25^\circ$ and of $3 - 4^\circ$ in ø for single telescopes. The same Whipple collaboration has discovered the first extragalactic source, the Markarian-421 Active Galactic Nucleus in 1992. The second similar source, the Markarian-501 has been discovered in 1995. All the above three sources were confirmed first by the HEGRA, then by the CAT and later by other collaborations. Note, that all currently known, firmly established VHE γ ray sources are discovered by such telescopes.
- The next step to improve the sensitivity was, similar to the development of the 1st generation telescopes, to use more than one imaging telescope. Application of N independently operating telescopes on relatively large distances from each other (so that Cherenkov light pools from individual air showers are seen only by single telescopes) will enhance the sensitivity of such an array by a factor of $\sqrt{N}$ compared to a single identical telescope. Unlike that the so-called stereo (or multiple view) approach was pursuing the simultaneous observation of a given shower by several telescopes. The stereo idea has been tested by the Durham, the Crimean Astrophysical Observatory, the HEGRA, the Whipple, the Telescope Array, and the CLUE collaborations/groups. Without going into details I will try to clarify the problem on the example of a few instruments:
  - The two Crimean telescopes are separated by 20 m, which on the one hand helps to lower the threshold, but on the other hand does not permit to fully use the information available in stereo viewing (at small distances between the telescopes the measured parameters of showers are strongly correlated, the telescopes measure almost the same image; such telescopes operate rather as a quasi-single large telescope with distributed reflector

area). By moving the telescopes apart from each other, till they are inside the Cherenkov light pool of a given shower, one will measure less and less correlation between the images and therefore one should expect that each telescope will add more into the total improvement of the signal/noise ratio.

- The Whipple collaboration has used the only place available in the vicinity of their 10m ø telescope on mount Hopkins, located $\sim$ 140m from the 10m, in order to install their second, the 11m ø telescope. The large distance between the telescopes and the inferior performance of the 11m (and its short life-time) provided a rather low coincident rate and so did not permit the full development and exploitation of the stereo technique.
- The latter has been successfully done by the HEGRA collaboration, which uses (along with a stand alone mode single $10m^2$ telescope) an array of 5 imaging telescopes, each with $8.5m^2$ reflector and 271 pixels, (4 at the corners of a square with a side length of $\sim$100m and the 5th at its centre) [7].

Note, that the problem of N independent telescopes set-up against that of the N coincident (stereo) telescopes has not yet been fully discussed in the literature. It seems that both techniques can provide comparable sensitivities although the stereo approach has valuable advantages, as the less background contaminated relative sample of γ's, somewhat better energy and angular resolutions and is therefore the preferred one, at least for energies $\geq$100 GeV.

2.2 The applicable energy range

The lower energy threshold of an imaging telescope depends on the

- reflector aperture and reflectivity
- light collection efficiency in the focal plane (type of the used light sensor, application of light collectors and their efficiency)
- pixelisation of the camera
- LONS
- trigger logic
- location altitude

In spite of complexity of factors influencing the threshold of an imaging telescope, one can outline an empirical relation, a guide line, allowing one to estimate (under the assumption of similarity to some extent of all telescopes) the threshold energy T (measured in TeV) as

$$T \simeq \frac{7}{S} \tag{1}$$

where S is the reflector surface area in m^2 (the T in (1) is the energy of γ events whose images will produce ~100 photoelectrons in the camera, which is enough, providing fine pixelisation, for reliable parameterization). The largest currently existing imaging telescopes measure successfully above the energy threshold of ~250-300 GeV up to energies of ~50 TeV. There still exists an unexplored gap in the electromagnetic energy scale between ~10-300 GeV due to lack of any measuring instruments there. The future arrays of the so-called 10m ø class Whipple type telescopes, the VERITAS, the CANGAROO-III and the HESS will extend the accessible energy range down to ~100 GeV [8].
Note, that the problem and advantages of sub-100 GeV γ astronomy were discussed already in 1977 [9].
In simulations [10] it was the first time shown that indeed one can use the imaging technique also for sub-100 GeV energies and that an optimally designed imaging telescope can provide successful measurements of γ sources above the lower energy threshold of a few tens of GeV. The 17m ø MAGIC telescope (see Fig.1) being currently under construction is designed to provide measurements above the dramatically low threshold of ~30 GeV (and above 10 GeV in future with very high quantum efficiency hybrid PMTs) [11].

2.3 The 17m ø MAGIC

The simple mechanical up-scale is not enough in order to build large telescopes, one needs to revise and to optimize most telescope parameters. For this purpose several innovative technologies were put forward by the MAGIC team and extensively tested during last few years. These are

- the carbon fibre light-weight reflector frame providing low inertia
- all Al made light weight diamond machined mirrors with internal heating
- *ns* fast analog signal transfer via optical fibres, providing very low time and amplitude dispersions
- computer-controlled active mirror control to counteract deformations of the reflector shape
- new hemispherical low gain 6 dynode PMTs and very low noise fast amplifiers
- 300 MHz flash ADCs for the data acquisition
- hybrid PMTs with very high quantum efficiency GaAsP photocathode

All the above mentioned innovative technologies, except for the last one still being under development, will be implemented in the current design of the telescope (note, that some of the above listed technologies are already implemented or are planned to be used in the design of the above mentioned arrays of telescopes [8]). MAGIC will be build within the experimental area used by HEGRA on Canary island La Palma (altitude 2200m a.s.l.). The reflector of

MAGIC will have a total area of $230m^2$ and consists of 920 square mirror tiles of spherical curvature each measuring $0.5 \times 0.5\ m^2$. Every 4 tiles will be set on a common motorized platform under computer control and adjusted to act as a single piece. Periodic optical measurements of the pointing of panels will provide feedback to the computer about the necessity of adjustment. The telescope will use a camera of ∼600 pixels, ∼400 of which will have a 0.10° ø and will be set in the central part. This will be surrounded by three rings of 0.20° ø pixels. The telescope will provide a very high sensitivity in the energy range $\sim 0.03 - 50$ TeV. For example, a 5σ signal from the Crab nebula, the standard candle in γ astronomy, can be measured in less than two minutes. Also one should mention the unique possibility for MAGIC to observe simultaneously with γ ray satellites in future the same targets in the overlapping energy range below 100 GeV in the sky. Combination of the very high sensitivity of MAGIC with the wide field of view of satellite detectors will allow one to carry out very efficient source searches. The MAGIC collaboration plans to build two more 17m ø telescopes at the same site in future within ∼150 m from the first one.

3 Conclusions

VHE γ ray astronomy is evolving fast. The handful of sources discovered in the past years and understanding of the development directions along with several arrays of γ ray telescopes being currently under construction give confidence about the future of γ ray astronomy as one of the powerful and fruitful branches in astronomy and astroparticle physics. Future γ ray observatories will measure with very high sensitivity in the energy range from a few tens of GeV up to $50 - 100$ TeV providing valuable information about the VHE processes in cosmic sources.

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Figure Caption

Fig.1. Schematic view of the 17m ø MAGIC telescope. The car and one of the 4.3m ø telescopes of HEGRA are shown at the bottom for comparison.

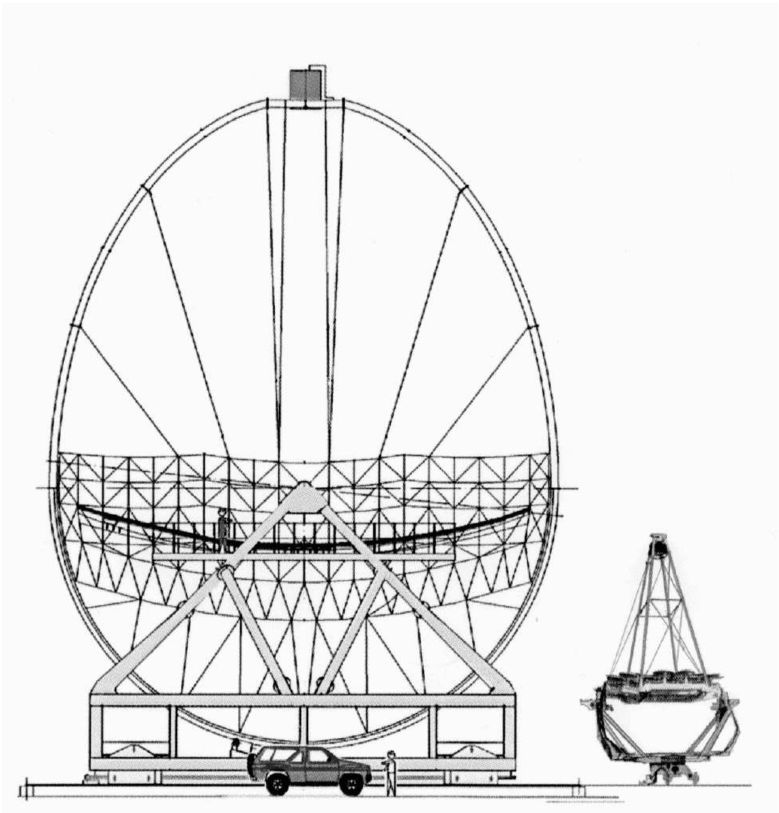

Fig. 1.