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STEREO ARRAY of 30 m Imaging Atmospheric Cherenkov Telescopes: A Next-Generation Detector for Ground-Based High Energy Gamma-ray Astronomy

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The construction of H.E.S.S., a system of four 12 m imaging atmospheric Cherenkov telescopes (IACT), has been completed recently in the Namib desert. This ground-based γ-ray detector of a new generation has an energy threshold around 100 GeV and a sensitivity of about 1% Crab flux. Similar stereoscopic arrays are currently under construction at Kitt Peak, Arizona, and at Woomera, Australia. Two telescopes of somewhat larger size of 17 m diameter are being built by the MAGIC collaboration at Canary Island of La Palma. Development of further instrumentation is primarily motivated by the various physics goals, perceived by the astrophysical community nowadays. Ultimately, a major ground-based Cherenkov facility for future dedicated γ-ray observations has to flexibly adapt to the observational requirements for a large variety of sources of very different nature. A stereo array of 30 m IACTs is such a detector, which allows to achieve an energy threshold as low as 10-20 GeV given a unique sensitivity, with a dynamic energy range expanding up to a few TeV. Basic results on performance and sensitivity for a single stand-alone 30 m imaging atmospheric Cherenkov telescope, as well as for a system of two and five such telescopes, derived from Monte Carlo simulations, are summarized here.

1. Introduction

Development of further instrumentation in the field of very high energy (VHE) γ-ray astronomy is primarily motivated by the physics goals as perceived by the astrophysics community today. Among those one has to mention (i) observations of the supernova remnants (SNR), which are the conjectural sources of VHE γ rays; (ii) continuous studies of the physics of the relativistic jets in active galactic nuclei (AGN); (iii) further investigations of morphology and spectra of γ rays from pulsar wind nebulae (PWN); (iv) the widening of the search for sources of pulsed γ-ray emission in VHE γ-ray band, etc. Such variety of physics enquiry can not be contented with only a single-type ground-based γ-ray instrument. Foremost the physics diversity of γ-ray emission mechanisms requires the essential observations appropriated in slightly different energy ranges. Thus for instance further observations of AGN and Pulsars necessitate the reduction of an instrumental energy threshold down to, at least, 10 GeV, whereas for detection of SNR assemblage a noticeable upgrade of sensitivity above 100 GeV is favored. The design of a major ground-based Čerenkov facility for future dedicated γ-ray observations has to conform to many requirements defined by peculiar energy spectral shapes, various angular extents, and strongly variable photon rates for the sources of an entirely different nature.

2. Telescope Design

The sensitivity of IACT at an ascertained energy is mostly determined by the total amount of Čerenkov light photons, which the telescope is able to collect from the γ-ray showers of that specific primary energy. In general, the larger the number of photons in the Čerenkov light flash recorded from an individual atmospheric γ-ray shower, the higher the quality of the shower image. Three basic parameters account finally for a total number of Čerenkov light photons registered from the atmospheric shower by a telescope. First of all it is the *geometrical size of the reflector*, A_o. The total number of recorded photons in a Čerenkov light flash scales linearly with respect to the geometrical area of the telescope's reflector. Given a recent progress in construction of IACT one can indeed envisage that construction of a 30 m parabolic Čerenkov telescope is indeed practical, considering both technical and financial aspects.

The Čerenkov light photons of an atmospheric shower which hit the telescope's mirrored surface, can be captured by an advanced imaging camera placed in the focal plane of the reflector. Using modern PMs and fast electronics it is now possible to convert registered photons into photoelectrons, and finally digitize the output signal in a number of ADC or FADC counts. The overall *efficiency of the photon-to-photoelectron conversion* is another basic parameter of the telescope design. For the conventional PMs this efficiency is about $< \epsilon >\sim 0.1$. In addition a substantial fraction of Čerenkov light photons emitted in atmospheric showers attenuates due to absorption and scattering of light in the Earth's atmosphere. We have considered here the *observational level* of $h = 1.8$ km. Finally the basic parameters of the telescope design determine the effective area of the telescope reflector $< A_o >=< \epsilon > A_o$, which is calculated with respect to a number of photoelectrons recorded by the camera. For the parameters chosen for the STEREO ARRAY the corresponding effective collection area is about $< A_o >\sim 70$ m^2.

3. Camera

The camera pixels of IACT are able to function under a hard load of night sky background light, yielding a photoelectron rate of about 200 MHz per pixel. The camera trigger, which embraces the PM signals within a certain (trigger) zone of the camera, is designed so that it eliminates accidental triggers due to Poisson-like fluctuations of night sky background light over a large number of camera pixels. For a 30 m telescope such criterion requires, for instance, a simultaneous registration of about 3 pixels with a signal exceeding a ∼6 photoelectron level, which is finally determined by the telescope and camera design. In addition one has to apply a size cut at the level of about 40 photoelectrons, which removes all images of low quality from the data sample on the costs of higher energy threshold. The minimal size of the recorded images is the final constraint on the actual energy threshold of the telescope. The energy threshold for a STEREO ARRAY is expected to be about 10-20 GeV.

Modern IACTs focus the light from the atmospheric shower onto a fine-granularity imaging camera. An angular size of the pixel (PM) and the total field of view are the basic parameters of camera configuration. For the 30 m diameter telescopes the low energy bound is about 10 GeV. The shower maximum of such low energy γ-ray showers is high above the observational level - 11 km. Therefore, the images of these showers have on average a very small angular size and in addition they are located very close to the center of the camera's field of view. For an accurate measurement of angular size of these images one needs to reduce the angular pixel size down to about 0.07° in order to increase a number of tubes involved in image parametrization. At the same time small pixel size suppresses the contamination of the night sky background light accumulated within a signal readout time window. The point spread function of a 30 m parabolic reflector degrades relatively fast at $\geq 1.5^\circ$ off the telescope optical axis. The pixel size of 0.07° for the field of view of 3° diameter is in fact a reasonable choice, which results in 1951 pixels.

4. System Layout

The HEGRA experiment has proven numerous advantages of the stereoscopic observations of γ rays above 500 GeV from the ground. H.E.S.S. was a extension of the HEGRA approach into lower energy range starting from 100 GeV. Further reduction in energy threshold down to ∼10 GeV also envisages making use of the stereoscopic approach. Large fluctuations in low energy showers noticeably degrade the quality of recorded

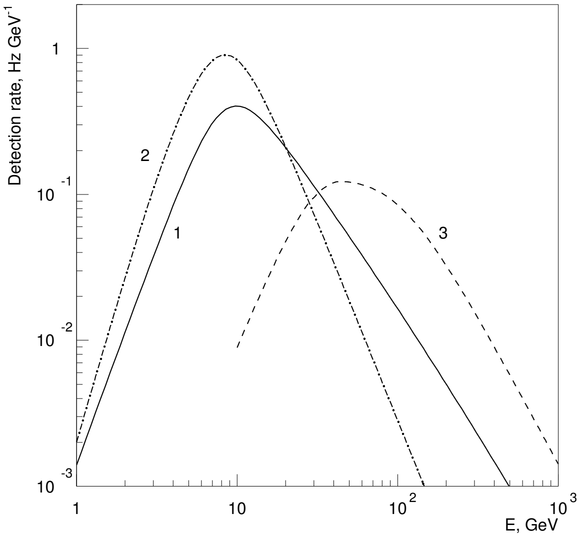

Figure 1. Differential detection rates of the γ rays (1), electrons (2), and cosmic rays (3).

Čerenkov light images. However, this can be substantially remedied using stereoscopic observations. To perform stereoscopic observations at low energies one needs to have at least two 30 m IACTs operating synchronically. The layout of the five telescopes was similar to that of the HEGRA layout but with a spacial separation between the telescopes of 100 m. A 100 m separation corresponds to a geometrical size of a Čerenkov light pool on the ground, which is in fact of about 100 m in radius.

5. Detection Rates & Analysis

Details on the simulations are given in [1]. The position of a peak in the differential detection rate of γ-ray atmospheric showers, which is calculated assuming the Crab Nebula energy spectrum, defines the effective energy threshold of the instrument (see Figure 1). The calculations have been done using the fluxes given in [1]. The differential detection rate of the proton-induced atmospheric showers peaks at substantially higher energy, within 30-90 GeV. The proton-induced atmospheric shower of that energy yields approximately the same amount of Čerenkov light as the γ-ray showers of about 10 GeV. The integral raw background rate for a system of two 30 m telescopes is expected to be about 1 kHz. The raw detection rates for a single 30 m telescope, as well as for a system of five such telescopes, are expected to be of 1.7 and 3.2 kHz, respectively.

The detection rate of the background cosmic rays and electrons usually exceeds by three orders of magnitude the expected rate from a Crab like γ-ray source. In order to extract the tiny fraction of the γ-ray events from the enormous amount of background contaminations one has to apply specific analysis cuts.

Orientation: Deflection of the reconstructed arrival direction of the γ-ray showers from the nominal source position is used for their orientational selection. At low energies the Čerenkov light images contain less light and are strongly affected by shower fluctuations. Therefore the results on reconstruction of the image orientation as well as the shower arrival direction substantially worsen. The angular resolution with two telescopes is of 0.3 degree for the γ-rays of 10 GeV. The angular resolution achieved with three images is 30% better than in the case of two images. It allows the reduction of the cosmic ray background contamination by a additional factor of 1.7. However, 3-fold triggers substantially decrease the rate of γ rays of energy close to the threshold.

Table 1. The integral rates (after cuts) and the minimum detectable γ-ray flux (above E_{th}) after 50 hrs of observations at 5σ level with a system of two 30 m imaging atmospheric Čerenkov telescopes.

E_{th}, GeV	R_{γ}, Hz	R_e, Hz	R_{CR}, Hz	$F_{min}(> E_{th})$, cm^{-2}s^{-1}
5	5.5	2.5	1.0	6.45×10^{-11}
10	4.7	1.5	1.0	3.00×10^{-11}
30	2.5	0.18	0.90	1.05×10^{-11}
50	1.7	0.06	0.68	6.65×10^{-12}
100	1.0	0.01	0.34	3.19×10^{-12}

Image shape: The most effective parameter of cosmic ray discrimination by the image shape in stereoscopic observations is a parameter of *mean scaled Width (m.s.w.)*. At least with two telescopes operating in a stereoscopic mode one can reconstruct the impact distance of the shower axis from each of the telescopes, and scale the actual transverse angular size of the image with the total amount of light in the image ($Size$-parameter) at that impact distance. One can suppress the rate of proton showers by factor of ~ 10 applying mean scaled Width cut of 0.91. This cut keeps about 35% of all registered γ-ray showers. The corresponding quality-factor is Q-factor=$\kappa_{\gamma} \cdot (\kappa_{CR})^{-1/2} \simeq 1.2$. High fluctuations in the image $Size$ of low energy events cause such rather modest rejection power.

6. Summary of Array Sensitivity

The sensitivity of the Čerenkov telescope in observations of the point-like γ-ray sources can be defined by the minimum flux of the γ rays, which can be detectable after 50 hrs of observations at the significance level above 5σ. The integral detection rates for the γ-ray, electron, proton showers, and the final results on the sensitivity calculations for the system of two 30 m telescopes are summarized in Table 1. It is worth noting that at low energies the electron background is dominant over the cosmic ray background. The electron component of the primary cosmic rays at energies about 5 GeV becomes, in fact, a major background. The images of electron and γ-ray showers are almost indistinguishable in shape, which make the electron background an absolute limiting factor for the detector sensitivity. Improved angular resolutions might help to reject contamination of the isotropic electron flux in observations of the point-like γ-ray source.

The stand-alone telescopes provide rather high γ-ray rates. However, due to limited rejection power the final sensitivity is by more than a factor of 2 lower than for a system of two telescopes, and by a factor of 5 as compared with the system of five telescopes. At the same time the increase in sensitivity with two to five telescopes is relatively modest. It is provided by the increase in collection area of the γ-ray showers, as well as a slightly better angular resolution for higher telescope multiplicity events.

An array of five 30 m telescopes is very close to the optimum detector for the γ-ray observations above 10 GeV. Such an array of detectors would be the most sensitive instrument in the field of ground-based high energy γ-ray astronomy in this energy range. The STEREO ARRAY might be considered as a major future detector for ground-based high energy γ-ray astronomy. Its construction and operation will enable scientists to perform high quality γ-ray observations from the ground, which will provide an overwhelming insight into the understanding of the mechanics of high energy γ-ray emission from the various physical environments in the Universe.

References

[1] A. Konopelko, Astroparticle Physics, in press (2005).