The potential of the ground based arrays of imaging atmospheric Cherenkov telescopes. II. Gamma ray flux sensitivities

F.A. Aharonian, W. Hofmann, A.K. Konopelko, H.J. Völk
Max-Planck-Institut für Kernphysik, D-69029 Heidelberg, Germany

We discuss the capability of '100 GeV' class imaging atmospheric Cherenkov telescope (IACT) arrays as future powerful instruments of ground-based gamma-ray astronomy. It is assumed that the array is gathered from individually triggered quadrangular 4-IACT 'cells' with a linear size of about 100 m. The multi-cell concept allows coverage of large detection areas economically, and at the same time effective exploitation of the stereoscopic approach of determination of the shower parameters using information obtained by several IACTs simultaneously. Determination of arrival directions of γ-ray primaries on an *event-by-event* basis with accuracy $\delta\theta \leq 0.1°$ combined with high suppression efficiency (at both the hardware and software levels) of the background hadronic showers by a factor of $\approx 10^3$, and large, up to $1\,\mathrm{km}^2$ collection areas, can provide minimum detectable energy fluxes of ≥ 100 GeV γ-rays from point sources down to $10^{-13}\,\mathrm{erg/cm^2s}$ which is about 3 orders of magnitude lower than the current sensitivities achieved by the satellite-borne detectors at MeV and GeV energies. High sensitivities of multi-IACT arrays would partially compensate the limited efficiency of the technique for all-sky surveys, as well as allow to study moderately extended ($\leq 1°$) γ-ray sources. IACT arrays with minimum detectable fluence of ≥ 100 GeV γ-rays $S_\gamma < 10^{-8}\,\mathrm{erg/cm^2}$ are well suited for effective exploration of highly sporadic nonthermal phenomena from different classes of astrophysical objects on time-scales from ≤ 1 s to several minutes.

1. Introduction

The high γ-ray detection rate and CR background suppression ability as well as good accuracy of reconstruction of arrival directions of primary γ-rays are three remarkable features of the imaging atmospheric Cherenkov technique which provide a solid basis for gamma-ray astronomy with ground-based detectors. The large collection area, $S_{\rm eff} \approx 3 \cdot 10^8\,\mathrm{cm}^2$, coupled with high ($\approx 99.9\%$) CR background rejection efficiency, both being achievable by a *single* IACT (for review see e.g. [1,2]), allow the detection of TeV γ-ray fluxes from point sources $F \sim 10^{-11}\,\mathrm{ph/cm^2s}$ at high confidence level during only one night of observations. The recent $\geq 10\sigma$ detections of γ-ray signals from the Crab, PSR B1706-44, Mrk 421 and Mrk 501 by the Whipple, CANGAROO, and HEGRA IACTs have proved these expectations to be true. These results imply that the *energy flux* sensitivities of the existing IACTs for 1 h of observations have reached the level of a few times $10^{-11}\,\mathrm{erg/cm^2s}$. Note that a similar flux can be only marginally revealed at GeV energies by the EGRET instrument on board of Compton GRO after continuous multi-week observations of high latitude sources [3]. Different approaches for the further development of the ground-based γ-ray detection technique are currently a matter of intensive theoretical and experimental study (see e.g. [4]).

In our previous paper, hereafter is referred as Paper 1, we have shown that a dramatic qualitative improvement of the IACT technique can be gained by the implementation of the stereoscopic approach of simultaneous detection of air showers by several IACTs separated at distances of about 100 m from each other. In particular, we have investigated the characteristics of a quadrangle $100 \times 100\,\mathrm{m}^2$ 'cell' consisting of four '100 GeV' class IACTs in its corners. The angular resolution $\delta\theta \leq 0.1°$ of the 'cell' provides suppression of the CR background based only on the *directional* information by a factor of $(max[2\delta\theta, \Delta\phi]/\Psi)^2$, where $\Delta\phi$ is the angular size (diameter) of the source, and Ψ is the diameter of the zone in the FoV of the camera where the trigger is organized ('trigger zone'). In the case of a point-like source ($\Delta\phi \ll \delta\theta$) the recommended 'trigger zone' is $\Psi \sim 3°$, and thus the CR background can be reduced by a factor of ≥ 200. For extended sources, namely when $\Delta\phi \geq \delta\theta$, the CR background rejection efficiency is determined essentially by the angular size of the source. In particular, it decreases with $\Delta\phi$ as $\Delta\phi^{-2}$ until $\Delta\phi \sim 1^{\circ}$; for more extended sources, obviously only the intrinsic features of the electromagnetic and hadronic cascades can be effectively invoked for the suppression of the CR background. Fortunately the IACT 'cells' do have sufficient γ/p separation power for the study of moderately diffuse γ-ray sources. In Paper 1 we have shown that the combined (at the hardware and software levels) efficiency of the rejection of cosmic ray protons and nuclei can reach a factor of at least 10^3 owing to the significant differences (in shape and intensity) between the Cherenkov light images of hadronic and electromagnetic showers, detected simultaneously by several IACTs of the 'cell'.

2. Detection rates

Effective suppression of the CR background based on the 'directional' and 'shape' criteria allows detection of $\geq 100\,\mathrm{GeV}$ γ-rays from point sources under almost background-free conditions (i.e. the number of γ-ray events is significantly larger than the number of detected CR induced showers) if the photon flux exceeds $10^{-11}\,\mathrm{cm^{-2}s^{-1}}$. This is illustrated in Fig. 1a where the detection rate for a power-law γ-ray flux from a point source

$$\frac{dF_{\gamma}}{dE} = A \cdot (\alpha - 1) \cdot (E/1\,\mathrm{TeV})^{-\alpha} \qquad (1)$$

with $A = 10^{-12}\,\mathrm{ph/cm^2sTeV}$ and $\alpha = 2$ is shown together with the CR proton and electron detection rates. All curves correspond to detection rates *after* the application of the software *directional* and *shape* cuts. Note that only a negligible part of the detected showers produced by cosmic ray nuclei survive after being filtered through the *shape* cuts chosen for the γ-ray domain (see Paper 1); therefore the detection rates of cosmic ray nuclei are not included in Fig. 1a. Meanwhile, at energies below several hundred GeV, the CR background is dominated by electromagnetic showers induced by cosmic ray electrons. These showers are indistinguishable from γ-ray showers, thus only the *directional* cuts can be used for reduction of the contamination of the γ-ray signal by background showers of electromagnetic origin. Moreover in the case of extended sources with angular size $\Delta\phi \geq 1^{\circ}$ the electron-induced showers remain as a part of the CR background which in principle cannot be removed, and thus is the most serious limiting factor for γ-ray flux sensitivities.

In the energy region where the CR background is dominated by electromagnetic showers produced by primary electrons, the signal-to-noise ratio for the γ-ray flux described by Eq.(1) is determined as

$$\frac{N}{\sqrt{B}} \approx \frac{F(\geq E)}{\sqrt{J_{\mathrm{e}}(\geq E)\Omega}} \cdot (S_0 t)^{1/2} \propto E^{2.1-\alpha}\,, \qquad (2)$$

where Ω is the solid angle corresponding to the angular resolution of the 'cell' (in the case of a point source) or the source angular size (in the case of an extended source); S_0 is the detection area of electromagnetic showers, and t is the observation time. Thus, due to steep spectrum of CR electrons, $J_{\mathrm{e}}(\geq E) \propto E^{-2.2}$ down to $E \sim 10\,\mathrm{GeV}$, a reduction of the energy threshold of the 'cell' well below 100 GeV can be justified for the specific task of studying astrophysical objects with differential power-law spectra essentially steeper than $E^{-3.2}$, or spectral cutoffs which can be expected for various reasons in the sub-100 GeV region. It is also interesting to note that due to the existence of the "unremovable" CR electron background, the further improvement of the rejection efficiency for hadronic showers (for example, by adding more IACTs in the 'cell' or using very high resolution imaging cameras) is not of practical interest. The discussed here quadrangle 4 IACT 'cell' with cameras of moderate 0.25° pixel size is already able to push the CR background down to a level which at energies around 100 GeV is dominated by electromagnetic showers produced by cosmic ray electrons.

The ratio of the CR electron and proton detection rates, $R_{\mathrm{e}}/R_{\mathrm{p}}$, depends strongly on the image *shape* cuts chosen for the separation of the γ-ray and proton domains. Since the requirements on the suppression of CR protons can be

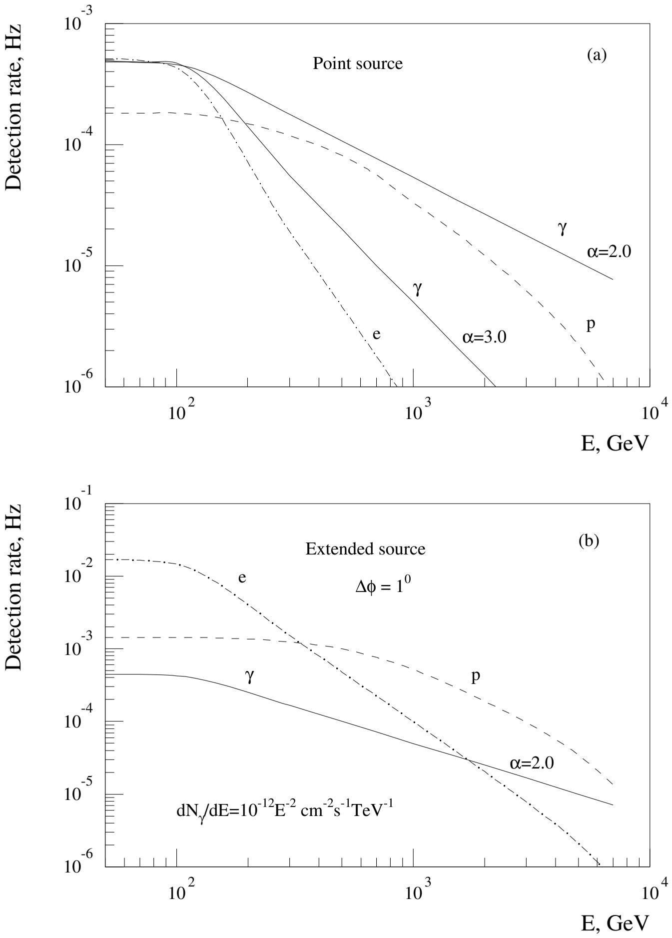

Figure 1. Detection rates of γ-rays (solid lines) as well as isotropic CR protons (dashed) and electrons (dot-dashed) by the 'cell' of IACTs after application of software image 'cuts'. The rates are shown as a function of the primary energy. (a) point source, and (b) '1°' diffuse source of γ-rays. In both cases $E^{-\alpha}$ differential power-law spectra of γ-rays, with normalization $F(\geq 100\,\mathrm{GeV}) = 10^{-11}\,\mathrm{ph/cm^2s}$ and power-law indices $\alpha = 2$ and $\alpha = 3$, are assumed. In the case of a point γ-ray source the combined 50% γ-ray acceptance is achieved by applying *directional* and relaxed *shape* cuts, while in the case of a '1°' source the same 50% γ-ray acceptance is a result of a strong *shape* cut (see the text).

different, depending on circumstances characterizing each specific case (e.g. the γ-ray flux, the angular size of the source, etc), the ratio $R_{\rm e}/R_{\rm p}$ may vary from case to case. In particular, to obtain sufficient statistics of γ-ray events from a weak point source, it may appear more profitable to apply relaxed *shape* cuts, since after the application of the *directional* cut the CR proton background is already suppressed by a factor of >200. On the other hand, the study of extended γ-ray sources may require a harder *shape* cut, since the latter remains the only means to improve the γ-ray signal by suppressing the proton induced showers. The influence of the two different *shape* cuts are demonstrated in Figs. 1a and 1b. While the 50% γ-ray acceptance in the case of '1°' source (Fig. 1b) is achieved by the application of strong *shape* cuts which remove approximately 99.7% of the hadronic showers ($\kappa_\gamma^{\rm (shape)} \approx 0.5$, and $\kappa_{\rm CR}^{\rm (shape)} \approx 3\cdot 10^{-3}$), in the case of a point source (Fig. 1a) the same 50% γ-ray acceptance can be maintained by applying a relaxed *shape* cut ($\kappa_\gamma^{\rm (shape)} \approx 0.8$, $\kappa_{\rm CR}^{\rm (shape)} \approx 1\cdot 10^{-2}$) since approximately 37% of γ-rays are already lost due to the application of the *directional* cut ($\kappa_\gamma^{\rm (dir)} = 0.63$; $\kappa_{\rm CR}^{\rm (dir)} = 4\cdot 10^{-3}$).

3. Minimum detectable fluxes

For the given observation time t_0 the minimum detectable flux of γ-rays $F^{\rm (min)}$ for an array of IACTs consisting of n_0 'cells' is determined from the following two conditions:

$$(i) \qquad \sigma = \frac{R_\gamma}{(R_{\rm e}+R_{\rm p})^{1/2}}(n_0 t_0)^{1/2} \geq m\,, \qquad (3)$$

and

$$(ii) \qquad N_\gamma = R_\gamma \cdot (n_0 t_0) \geq N_0, \qquad (4)$$

where R_γ, $R_{\rm p}$, and $R_{\rm e}$ are respectively the rates of detected γ-rays (signal), and CR protons and electrons (background) shown in Fig. 1a,b.

Eq.(3) requires sufficiently high confidence level of the detected γ-ray signal, and Eq.(4) implies sufficient statistics of detected γ-ray events. In this paper we choose the following numbers: $m=5$ and $N=100$ (detection of the signal at

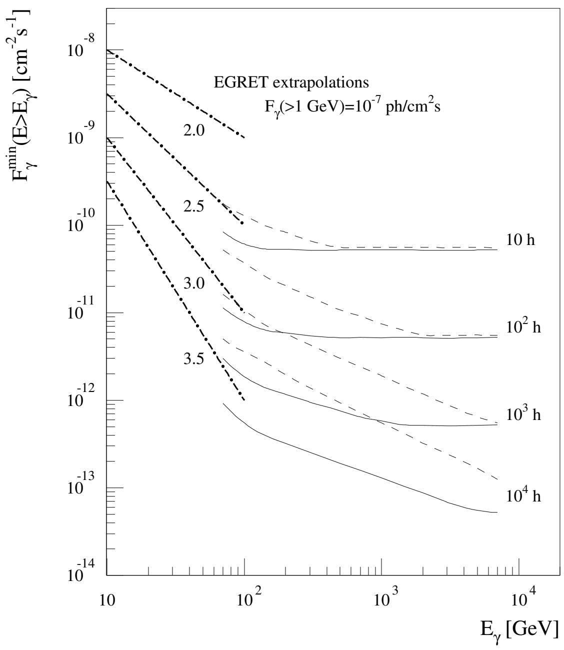

Figure 2. The minimum detectable fluxes of γ-rays from a point source (solid lines) and a '1°' source (dashes) by the IACT array for different exposure times $n_0 t_0$ indicated at curves. The extrapolations of a GeV γ-ray flux of a typical EGRET source into the TeV region for different differential power-law indices α are also shown. The calculations correspond to the requirement of a $\geq 5\sigma$ γ-ray signal with at least 100 detected γ-ray events.

the level of at least 5σ provided that the number of detected γ-ray events exceeds 100). Note that for the given configuration of the the IACT 'cell', $F^{\rm (min)}$ depends only on the product $n_0 t_0$ (hereafter called exposure time) which enters in $F^{\rm (min)}$ linearly if the condition (ii) dominates over the condition (i), and as $(n_0 t_0)^{1/2}$ in the opposite case. Due to the limited time of observations for a given source, typically $t_0 \leq 100\,$h per a year, and for a reasonable number of 'cells' in the array, $n_0 \leq 100$, the product $(n_0 t_0)$ cannot exceed $10^4\,$h. Thus, the extreme value of $n_0 t_0 = 10^4\,$h corresponds to long-term (several-week) observations of a chosen target with a huge $1\,{\rm km}^2$ array consisting of 100 'cells'. Modest exposure times, e.g. $n_0 t_0 = 10\,$h, can be interpreted as few nights

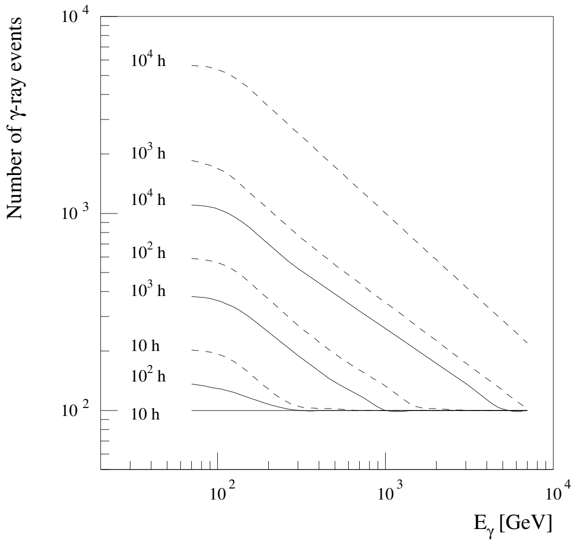

Figure 3. The number of detected γ-ray events from a point source (solid lines) and a '1°' source (dashes) corresponding to the minimum detectable fluxes of γ-rays shown in Fig.2.

of observations of a source with one IACT 'cell' or ≈ 5 min observation by a $1\,\mathrm{km}^2$ array.

The results concerning the minimum detectable γ-ray fluxes from a point source and the '1°' source calculated for different values of $(n_0 t_0)$ are presented in Fig. 2. Note that for small values of the exposure time, $n_0 t_0 \leq 100\,\mathrm{h}$, the minimum detectable γ-ray flux $F_\gamma^{(\min)}(\geq E)$ slightly depends on the energy, especially in the case of a point source, the reason being the low statistics of detected photons. This is seen clearly in Fig. 3 were the expected number of γ-rays $N_\gamma(\geq E)$, attributed to the curves for $F_\gamma^{(\min)}$ in Fig. 2, are shown; the flat (energy independent) regions of $F_\gamma^{(\min)}$ always correspond to $N_\gamma = 100$ (see Eq.(3)). Comparison of minimum detectable fluxes of γ-rays from a point and '1°' sources shows that they are comparable for small values of the exposure time $n_0 t_0$ (since the flux limiting factor is determined essentially by ther statistics of γ-ray events), but at large values of $(n_0 t_0)$, when the CR background rejection determines the level of detectable γ-ray fluxes, the difference becomes noticeable.

At large $n_0 t_0$, the minimum detectable γ-ray flux $F^{(\min)}$ from a point source is determined predominantly by the condition (i) requiring $\geq 5\sigma$ appearance of the signal. Assuming, for simplicity, that the γ-ray hardware detection efficiency as well as the acceptance for γ-ray showers after application of software 'cuts' are constant over the whole energy region, we should expect for $F^{\min}$ an energy dependence roughly as $F^{(\min)}(\geq E) \propto \sqrt{J_{\mathrm{CR}}(\geq E)}$, i.e. $\propto E^{-1.1}$ and $\propto E^{-0.85}$ at energies below and above a few hundred GeV, where the primary electrons and protons determine the level of the CR background, respectively. In fact, at energies around 100 GeV $F^{(\min)}$ shows a stronger energy dependence which reflects the fast reduction of the detection efficiency below 100 GeV, especially in the mode when a shower is detected by all 4 IACTs of the 'cell' (see Fig. 5 in Paper 1).

In Fig. 2, together with minimum detectable VHE γ-ray fluxes, we show also, for comparison, the power-law extrapolations of the fluxes of the GeV (EGRET) γ-ray sources into the TeV energy region, assuming for the flux of a typical EGRET source $F(\geq 1\,\mathrm{GeV}) = 10^{-7}\,\mathrm{ph/cm^2s}$. We may conclude that if the energy spectra of EGRET sources extend into the TeV region, large multi-cell arrays of IACTs can easily reveal all these sources for reasonable observation times (e.g. $n_0 t_0 \sim 10^3\,\mathrm{h}$) provided that the differential power-law index $\alpha \leq 3.5$ for point sources and $\alpha \leq 3$ for '1°' objects.

It should be noted, however, that almost all EGRET sources are poorly explained theoretically, and that, as a rule, the current models suggested for these sources do not provide definitive predictions for the expected γ-ray fluxes in the VHE domain. On the other hand it is quite possible that many classes of galactic and extragalactic objects release their nonthermal energy most effectively at TeV rather than at MeV-GeV energies [5]. From this point of view the *energy flux sensitivity* which can be defined as $f_{\mathrm{E}}(E) = EF(\geq E)$ may serve as an objective parameter, especially concerning the observability of the sources in different energy bands.

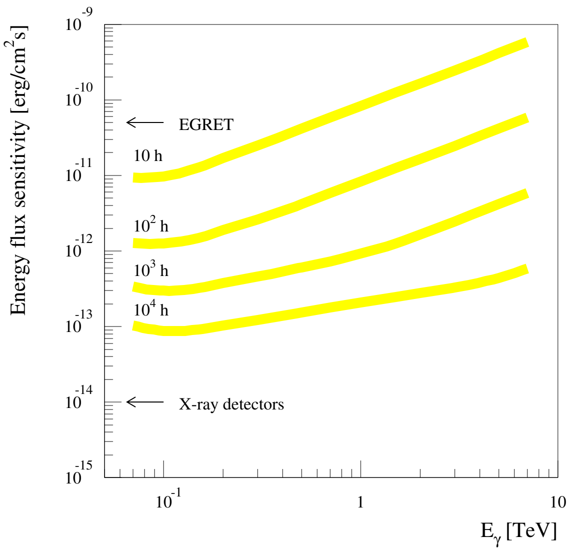

Figure 4. The minimum detectable energy fluxes of γ-rays $f_{\rm E} = E \cdot F(\geq E)$ for the IACT array from a point source for different exposure times $n_0 t_0$ shown at the curves. The sensitivities of the EGRET instrument at GeV energies as well as the sensitivities of modern X-ray detectors at keV energies are also shown. The calculations correspond to the requirement of detection of a $\geq 5\sigma$ γ-ray signal with $N_\gamma \geq 100$ detected photons.

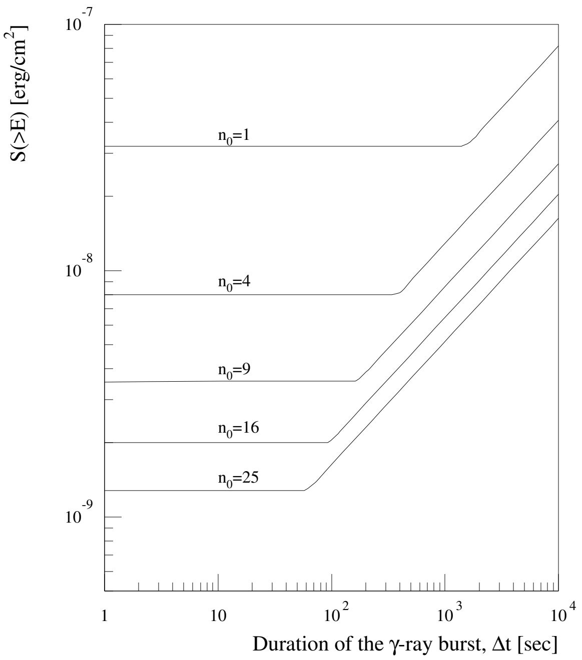

Figure 5. The minimum detectable fluence of γ-rays $S_\gamma = f_{\rm E} \cdot \Delta t$ above 100 GeV assuming a constant photon flux during the burst. The calculations correspond to the detection of a $\geq 5\sigma$ burst with at least 10 detected γ-ray events.

In Fig. 4 we show the point source sensitivities $f_{\rm E}(E)$ of an IACT array calculated for different values of $n_0 t_0$. For comparison the levels of characteristic sensitivities of the currently operating γ-ray detector EGRET at GeV energies and X-ray detectors like ROSAT at keV energies, are also indicated. From Fig. 4 we may conclude that future large $1\,{\rm km}^2$ arrays of '100 GeV' class IACTs would allow the detection of $\geq 100\,{\rm GeV}$ γ-ray fluxes down to $10^{-13}{\rm erg/cm^2 s}$. This will allow to probe the apparent (4π) luminosities of γ-ray sources at the level of $L \sim 10^{31}(d/1\,{\rm kpc})^2{\rm erg/s}$ which is impressive even by the standards of the radio, optical and X-ray branches of astronomy.

High sensitivities of multi-IACT arrays would compensate, at least partially, a serious disadvantage of the IACT technique, namely its limited capability for an all-sky survey. Indeed, with an array consisting of approximately 10 IACT 'cells' it would be possible, for example, to provide 5σ signals of potential 100 GeV γ-ray emitters at the $\frac{1}{10}$ Crab flux level with sufficient $(N_\gamma \geq 100)$ photon statistics in only a few hours of observations.

Also, due to their high detection rate capability the multi-IACT arrays are effective instruments in the search for possible episodic or burst-like phenomena. In Fig. 5 we show the minimum detectable fluence of $\geq 100\,{\rm GeV}$ γ-rays as a function of the duration Δt of a γ-ray episode calculated assuming a constant photon flux during the burst activity of the source Δt: $S(\geq E) = f_{\rm E} \times \Delta t$. The curves in Fig. 5 correspond to five different configurations of the array consisting of 1, 4, 9, 16 and 25 IACT 'cells'. The results are shown for time scales Δt from 1 s to 10^4 s which are typical for the phenomenon of gamma-ray bursts (GRBs) (see e.g. [6]). Note that the horizontal (time-independent) parts of the curves corresponding to short episodes are the result of the requirement to have at least 10 detected γ-ray events during the burst, while the dependence $S(\geq E) \propto (\Delta t)^{1/2}$ at large Δt corresponds to the regime where the requirement of detection of a $\geq 5\sigma$ signal dominates.

Fig. 5 demonstrates that the telescope arrays consisting of several IACT 'cells' would be able to detect the VHE counterparts of GRB events with a typical value of the fluence at MeV energies between 10^{-7} to $10^{-3}\,\mathrm{erg/cm^2}$, even if only a small part of the total energy of the burst is released in $\geq 100\,\mathrm{GeV}$ photons. On the other hand, such arrays can explore new types of highly sporadic nonthermal phenomena from different classes of astrophysical objects which at MeV and GeV energies may appear well below the sensitivities of current (like BATSE and EGRET GRO) or currently planned γ-ray burst detectors.

4. Evaluation of the energy spectra

The energy resolution of a single IACT is estimated as approximately 30–40 %. This allows estimation of with acceptable accuracy the integral γ-ray fluxes as well as the slope of power-law spectra of primary γ-rays [7]. The statistical uncertainty in the flux determination is estimated as $\delta F/F \approx 1/m$, where m is the number of standard deviations above the CR background. Thus even a 5σ detection of the signal already provides $\approx 20\%$ statistical accuracy for the flux estimate. At the same time, the capability of a single IACT is not sufficient for the correct evaluation of spectra with strong spectral features. For example, in the case of the power-law γ-ray spectrum with an exponential cutoff at energy $E^\star$,

$$dF/dE \propto E^{-\alpha} \cdot \exp(-E/E^\star)\,, \tag{5}$$

the reconstructed points may extend well beyond the cutoff energy $E^\star$ and the spectrum could be misinterpreted as a pure power-law with an erroneous slope [7].

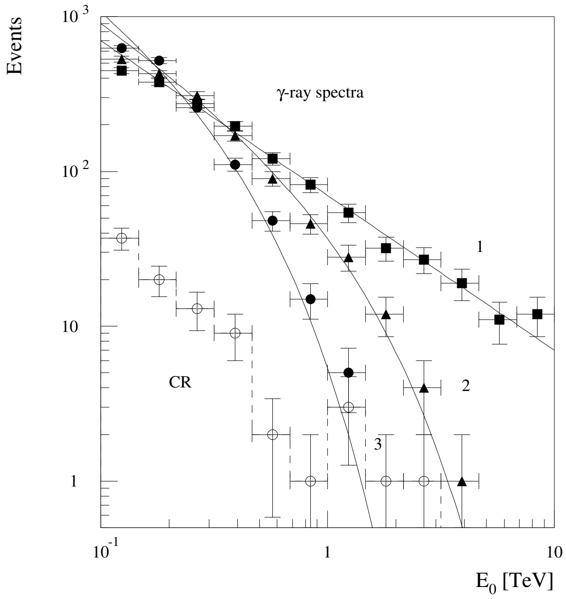

Figure 6. The reconstructed spectra of γ-rays detected during the exposure time $n_0 t_0 = 50\,\mathrm{h}$. The primary γ-ray spectra were taken in the form described by Eq.(5), for a power-law index $\alpha = 2.2$ and for 3 different values of the cutoff energy: 1 – $E^\star \gg 1\,\mathrm{TeV}$ (reconstructed fluxes are given by filled quadrangles); 2 – $E^\star = 1\,\mathrm{TeV}$ (filled triangles); 3 – $E^\star = 300\,\mathrm{GeV}$ (filled circles). For comparison the CR background, remaining after the application of software image 'cuts', is shown by open circles.

The capabilities of the 'cell' of IACTs for spectroscopic purposes are much broader. The rejection of the CR background based on the very effective γ/proton separation by 'directional' and 'shape' criteria, together with the ability to reconstruct precisely the shower impact point, allows determination of the energy of *individual* γ-ray showers with an accuracy of $\delta E/E \leq 20\%$ at almost CR background free conditions, if the flux of γ-rays from a point source exceeds $F(\geq 100\,\mathrm{GeV}) = 10^{-11}\,\mathrm{ph/cm^2 s}$. This allows evaluation of the differential fluxes of γ-rays with high accuracy without *a priori* assumptions about the shape of the primary spectrum, if, of course, the energy-dependent characteristics of the IACT 'cell' like the hardware detection efficiency and the software γ-ray acceptance are well understood. In particular, the Monte Carlo calculations show that the IACT 'cell' is able to reproduce correctly spectral features like the sharp cutoffs which are expected in the primary spectrum between 100 GeV and 1 TeV from different classes of astrophysical objects. In Fig. 6 we show the primary and the reconstructed differential spectra of γ-rays having a spectral shape described by Eq.(5) with an exponent $\alpha = 2.2$ and energy cutoffs at $E^{\star} = 300\,\mathrm{GeV}$, $1\,\mathrm{TeV}$, and $\gg 1\,\mathrm{TeV}$. It is seen that for the assumed integral flux of γ-rays above 100 GeV $F(\geq 100\,\mathrm{GeV}) = 10^{-10}\,\mathrm{ph/cm^2s}$, a $t_0 = 50\,\mathrm{h}$ observation time of the source by only one 'cell' of IACTs is sufficient for correct reproduction of the shape of the primary spectrum, including the region of the exponential cutoff. Since the detected γ-ray fluxes are well above the level of the CR background, the time needed for an adequate spectral measurements by an array consisting of n_0 'cells', is only $50/n_0\,\mathrm{h}$.

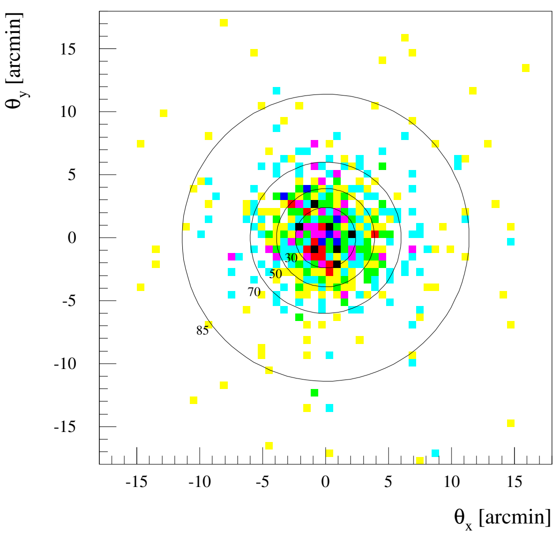

Figure 7. Two dimensional distribution of the reconstructed arrival directions of γ-rays from a point source with E^{-2} spectrum. The circles indicate the $30\%, 50\%, 70, 85\%$ boundaries of the accepted γ-rays.

5. Study of the source angular size

IACT arrays can provide the best angular resolution in gamma-ray astronomy from MeV energies to ultra-high energies. The determination of arrival direction of primaries on an *event-by-event* basis with an accuracy $\delta\theta \leq 0.1°$ is achievable even by a 'cell' of IACTs equipped with relatively modest cameras with a pixel size around $0.25°$ (see Paper 1). In the case of sufficient photon statistics (about 100 events detected) this feature allows to localize the position of point sources with an accuracy ≤ 1 arcmin, as well as to study the angular distribution of moderately extended diffuse γ-ray sources with angular size $\leq 1°$.

In Fig. 7 we present the angular distribution of the reconstructed arrival directions of γ-rays from a point source detected by the IACT 'cell'. The circular contours drawn around the position of the point source indicate the fractions ($30\%, 50\%, 70\%, 85\%$) of detected γ-rays with reconstructed directions within the corresponding circles. Fig. 7 shows that more than 50% of the reconstructed γ-ray events are at the distance of a few arcminutes from the exact position of the source, which opens a promising way to study the spatial distributions of extended γ-ray sources in arcminute scales. This possibility is demonstrated in Figs. 8ab, where the distributions of the angular distance of reconstructed arrival directions of γ-rays from the center of extended sources are shown. It is assumed that all sources have a circular shape in the two-dimensional plot with a homogeneous distribution of the photons inside. Note that the histogram 1 in Fig. 8a corresponds to the two-dimensional distribution of reconstructed γ-rays from a point source shown in Fig. 7. From Fig. 8a we may conclude that for sufficiently high statistics of detected γ-rays it is possible to measure the size of an extended γ-ray source of $\Delta\phi \leq 0.1°$ with an accuracy ≈ 1 arcmin.

For more extended sources, the unavoidable background due to the electromagnetic showers produced by cosmic ray electrons, especially at $E \sim 100\,\mathrm{GeV}$, prevents the study of the spatial distribution of the source under CR background-free conditions, unless the γ-ray flux exceeds $F(\geq 100\,\mathrm{GeV}) = 10^{-10}\,\mathrm{ph/cm^2s}$. Therefore de-

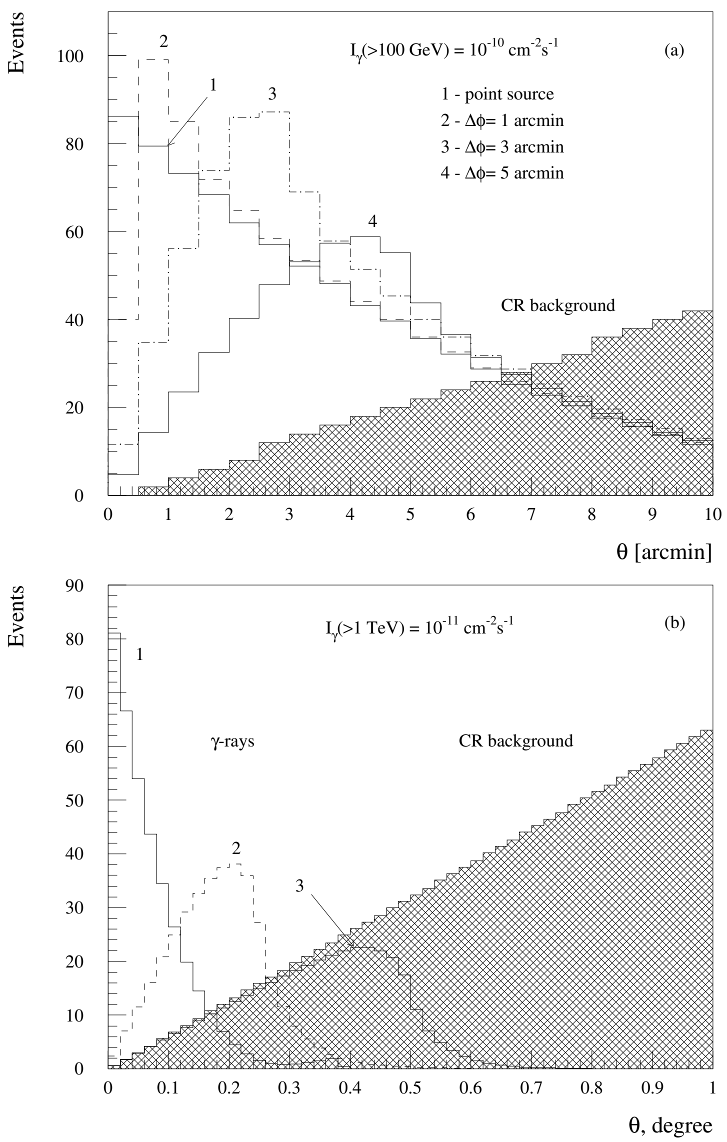

Figure 8. The distributions of the angular distance of reconstructed arrival directions of γ-rays from the center of sources with different angular extension: (a) $\Delta\phi$ =0, 2 arcmin, 6 rcmin, 10 arcmin; (b) $\Delta\phi$ = 0, 0.5°, 1°. The exposure time in both figures is $n_0 t_0$ = 50 h. A differential energy spectrum E^{-2} with normalization $F(\geq 100\,\mathrm{GeV}) = 10^{-11}$ ph/cm^{2}s has been used in both figures, however in the case (b) only γ-rays above 1 TeV were analyzed.

tailed information about the angular distribution of the photons can be obtained only on the basis of high statistics of detected γ-ray events.

Since the energy spectrum of CR electrons is steep, the extended-source study can in some cases be done more effectively at higher (TeV) energies, especially for γ-ray sources having very hard spectra (e.g. with differential power-law index $\alpha \leq 2$). In Fig. 8b we present the reconstructed angular distributions using only the data set of $\geq 1\,\mathrm{TeV}$ γ-rays from sources with angular extension $\Delta\phi = 0°, 0.5°, 1°$. The energy spectrum of γ-rays for all 3 cases was assumed to fall like E^{-2} with an integral flux $F(\geq 1\,\mathrm{TeV}) = 10^{-11}\,\mathrm{ph/cm^2s}$. We see from Fig. 8b that for $\Delta\phi \geq 1°$ the γ-ray events would be heavily absorbed in the CR background produced essentially by CR protons. Thus the detection of a $10^{-11}\,\mathrm{ph/cm^2s}$ flux of TeV γ-rays can be achieved only for a good statistic of γ-ray events, namely $n_0 t_0 \geq 100\,h$ (see also Fig. 2).

6. Summary

Future large arrays consisting of '100 GeV' class IACTs and covering up to $\sim 1\,\mathrm{km}^2$ area will be able to probe, typically during several weeks of continuous observations, the potential VHE emitters of $\geq 100\,\mathrm{GeV}$ γ-ray signals at an energy flux level of $f_{\mathrm{E}} = E^2 dF/dE \sim 10^{-13}\,\mathrm{erg/cm^2s}$. This is about 3 orders of magnitude lower than the sensitivities achieved at MeV and GeV energies by the COMPTEL and EGRET instruments on board of Compton GRO. The high sensitivity of multi-IACT arrays would partially compensate the inefficiency of the technique regarding all-sky surveys, due to the small FoV of telescopes. The 100 GeV γ-ray sources with a strength of 100 milliCrab can be revealed in an observation time of less than 1 h.

The high detection rate of multi-IACT arrays will allow exploration of highly sporadic nonthermal phenomena from different classes of astrophysical objects which may appear well below the sensitivities of satellite-borne detectors at MeV and GeV energies.

With $\delta\theta \leq 0.1°$ the IACT arrays may provide the best angular resolution in gamma-ray astronomy from MeV to ultra-high energies. In combination with high γ-ray detection rate and effective CR background suppression this allows to study effectively the spatial distribution of moderately extended sources with angular size up to $\sim 1°$.

The determination of the energy of *individual* γ-ray primaries with accuracy $\Delta E/E \leq 25\%$ makes practicable appropriate spectroscopic measurements, in particular searches for features like sharp cutoffs in the spectra of γ-ray sources.

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