

Gamma-ray astronomy with ground-based array detectors: status and perspectives

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Abstract. The basic concept and the status of currently operating ground-based array detectors for VHE gamma-ray astronomy will be presented and compared with imaging air Cherenkov telescopes. Also an outlook of future prospects will be given.

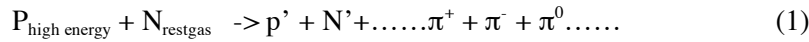
1. Introduction

The window of very high energy (VHE) gamma-ray (shortcut γ) astronomy has been opened by the detection of TeV γ s from the Crab nebula [1] in 1989. Since then this field of research is steadily expanding and many more sources have been discovered and important physics information about the ultra-relativistic universe have been obtained. Although γ s are only a very small fraction of the cosmic ray (CR) flux steadily bombarding the earth, they are the currently best suited ‘messengers’ of ultra-relativistic processes in our universe. Charged CRs are not suitable because they are deflected by the weak galactic magnetic fields and cannot be correlated with specific cosmic sites (stars, galaxies....). The only exceptions might be CRs above 10^{19} eV. Only neutral particles – γ s, ν s, neutrons and may be dark matter particles—are suited as cosmic messengers to be correlated with specific sites. Dark matter particles still await their discovery and energetic neutrons might allow one at most to explore the very close-by universe because of their short life-time. Neutrinos are in principle also promising messengers because they are, as weakly interacting particles, not absorbed in the universe, but their small interaction cross-section makes detection extremely difficult and require huge detector volumes. It is hoped that the current efforts to build such detectors will eventually lead to the detection of the first source emitting high energy neutrinos (Up to now only two cosmic HE neutrino emitters have been detected, the Sun and SN 1987A). Gamma-rays have specific features making them particularly suitable to act as messengers:

- They have infinite lifetime
- They fly on straight lines from the point of generation to the earth, i.e. VHE γ s can easily extrapolated back to the sources.
- As massless particles they fly with the speed of light and can transmit correct timing information from process at the origin.
- Gamma rays are not accelerated in classical ways like charged particles and thus require higher energy ‘parent’ processes for generation.

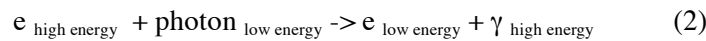
The possible production processes of VHE γ s are:

- Hadronic processes such as for example a high energy proton (expected to be accelerated by shock waves) interacting with some matter (normally close to or part of some stellar object) leading to dominantly pion production as



with the charged pions decaying into muons ($\rightarrow e + \nu$) and ν s and the π^0 into $\gamma\gamma$. Reaction (1) stands for a number of hadronic interaction channels with decay channels leading both to VHE ν and γ production. The simultaneous discovery of both, γ and ν , would be proof of acceleration of hadrons, which in case of galactic origin, could eventually also show up as the charged CRs detected on earth.

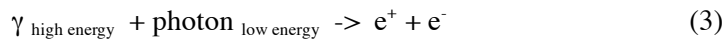
- Leptonic production of high energy electrons upscattering low energy photons via inverse Compton scattering



Sufficient target photons can be found close to stellar object (thermally generated photons) or generated by synchrotron radiation from the accelerated photons or even from the cosmic microwave background (CMWB).

- Possible other production processes can be the decay and subsequent hadronisation of superheavy particles – Topological defects or Relic particles from the early universe- or from interactions of ultrahigh protons with the CMWB.

The observation range of long distance cosmic γ s above a few tens of GeV is limited by their possible interaction with various low energy cosmic photon fields (EBL) such as the CMWB, visible and infrared starlight, cosmic radio background etc.



with the cross section peaking close above threshold of e^+e^- production. Fig 1. shows an early calculation of the absorption length as a function of the γ energy. Reaction (3) is of importance for ground-based γ detection. Around 10^{15} eV the observation range is limited to the very close by universe and only ν astronomy would be viable for the observation of distant processes. Somewhere below 10^{11} eV – the exact value is unknown because of the unknown IR background- the universe becomes highly transparent and one could in principle detect sources up to high redshifts. To reach such a low threshold is an important challenge for all detectors for VHE γ astronomy.

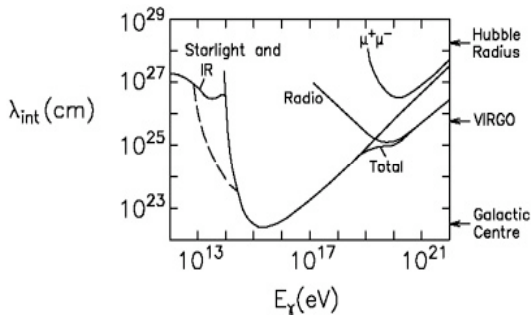


Fig. 1 Attenuation length of cosmic γ s in the universe as a function of energy

2. The general array detector concept

The earth atmosphere is an effective shield against cosmic radiation and thus prevents direct observation of γ s from ground. In the KeV/MeV energy domain the best detectors for γ -astronomy are satellite borne ones with an anticoincidence shield against the dominant charged CRs. At VHE the γ flux is much lower and ground-based detectors using indirect detection methods with collection areas exceeding that of satellite borne ones by many orders of magnitude have to be used. All current high-

energy detectors follow the calorimetric principle. The atmosphere acts as an absorber (air mass 1: 27 radiation length (rl), 11 hadronic absorption length) and some secondary quantity (shower tail particles, Cherenkov light, Fluorescence light, possibly Radio waves) related to the incident direction and energy can be measured with a suitable detector. High energy particles interact with nuclei of the top layer of the atmosphere and lose their energy by a multiple reaction chain resulting in extended air showers, in case of γ s electromagnetic (em) showers with very few hadronic particles and muons

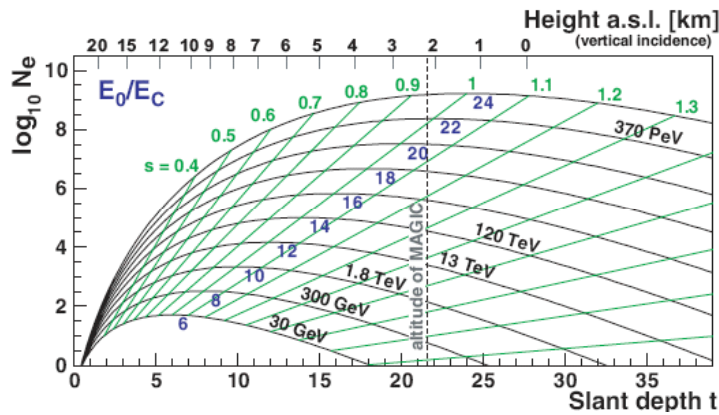


Fig. 2. Monte Carlo simulation of secondary electron multiplicity in an em shower in the atmosphere as a function of the slant depth (in units of rl), parameter initial γ energy.

of shower tail particles reaching ground. Radio or air fluorescence detection is still unsuited because of the very low signal intensity from VHE showers. The Cherenkov light is normally detected by so-called imaging air Cherenkov telescopes (IACT) with a very small field of view (FOV) allowing up to now observations of only discrete source locations (with one exception). The incident direction and energy is derived from the analysis of the shower image; for details of the concept, see for example overview article ref [2].

A single telescope, or if affordable, several ones are sufficient to observe sources. Shower tail detectors, here called ground-based array detectors, are normally sensitive to the charged shower tail particles. Normally the direction of the incident particle is determined by time of flight measurements of the scattered tail particle and the energy by the density of the tail particles. The main advantages of array detectors are that they allow monitoring a large section of the sky and that they are sensitive for 24 h a day. Their main disadvantages are the high threshold because of the requirements that sufficient tail particles have to reach ground, the poor angular and energy resolution close above threshold and also the modest γ /hadron separation power. Table 1 compares the essential parameters of state of the art VHE array detectors and IACTs. The basic sensors for arrays are nowadays either scintillation counters (plastic or liquid scintillators) or encapsulated water Cherenkov detectors in form of water tanks or large ponds subdivided into light-tight sections. In all cases the scintillation light or Cherenkov light is detected by high sensitive photomultipliers (PMT). The high costs, particularly for scintillation counters, normally limit the area, respectively the active area coverage, leaving often only the choice of either a large detector with very modest active detector coverage resulting in a very high threshold or in a small area with a high active detector coverage and a lower threshold. From current results, mainly from observations with IACTs, we know that a low threshold, well below the 10^{13-14} eV threshold of past array detectors is absolutely essential for the future use of array detectors.

Figure 2 shows a MC simulation of secondary electrons along the shower depth (in units of rl) as a function of primary γ energy. Using the somewhat arbitrary requirement of detecting at least 100 particles to trigger and retrieve useful information about the incident γ one can deduce the threshold in zenith for an array detector for a given altitude and active area fraction as well as the zenith angle

while hadronic particles produce so-called hadronic showers, which nevertheless are dominated by the em sub-showers at the tail with a significant admixture of muons and ν s. As ν s escape undetected, only a fraction of the incident energy is dumped into the atmosphere. One of the main challenges of ground-based detectors is the selection of γ -candidates from the many orders more frequent hadronic cosmic particles.

The VHE detectors follow two main principles: a) detection of Cherenkov light, dominantly produced by the ultra-relativistic particles in the shower maximum and b) the detection

dependence from the overburden of air mass as function of Θ . The threshold of array detectors rises with a very steep function of the zenith angle, $\approx (\cos \Theta)^{-(5-7)}$. Due to shower fluctuations a threshold of 100 particles does not correspond to a fixed energy. For defining the threshold one commonly uses in the γ -astronomy community the peak of the observed differential spectrum.

At the shower tail there are about seven times more low energy secondary γ s than electrons. Thus, by using appropriate converters, which do not absorb too many electrons one can somewhat lower the threshold.

Table 1: Comparison of main parameters of a typical array detector and an air Cherenkov telescope

	Ground-based array	ACT
	<i>24 h, year round (except of snow coverage)</i>	<i>$\approx 10\%$ per 24 h day, good atm, conditions needed</i>
Up-time		
All sky monitoring	1-3 sterad monitoring	Very limited FOV, msterad
Typical threshold	1-10 TeV at 2000m asl	100-200 GeV at 2000 m asl
Typical threshold dep. on Θ (=ZA)	$\approx (\cos \Theta)^{-(5-7)}$	$\approx (\cos \Theta)^{-2.7}$
Detection area dependence on Θ	shrinks with $\approx \cos \Theta$	Increases with $\approx 1/\cos \Theta$
Typical detection area for VHE γ observation	0.01- 0.1 km ²	0.04-0.05 km ² in zenith position
Energy resolution close above threshold	Very modest	20-25% close above threshold
Angular resolution close above threshold	0.5-1°	0.05-0.2° close above threshold
Check of reference system	Shadow of the moon	Starguider camera
γ /hadron separation power	Very low to low	High to very high
Robustness	Very robust, normally no moving elements	Moving elements, needs steady operator presence

3. Current experiments and some selected results

Until 10-15 years ago array detectors were the main ‘workhorse’ for the search of γ -emitting sources, which were assumed to be also sources of CRs. The basic detector comprised an array of scintillation counters of rather coarse sampling of <0.5% to about 2% active area coverage. All of these experiments failed to detect γ -sources. Reasons were a much too high threshold (can be immediately deduced from fig. 2 when requiring a minimum of about 100 secondary particles hitting the active material) and a much too poor γ /hadron separation. Other effects contributing to the failures were operation at low altitude (large overburden), very modest angular resolution and energy resolution close to the threshold. Extragalactic sources were anyhow impossible to detect because of the absorption of VHE γ s due to the interaction with the EBL. Gradually, experiments moved to higher altitude and increased the active detector fraction eventually to practically 100%. Currently only three large array detectors with a sufficiently low threshold to detect the strongest galactic and low redshift sources are operating worldwide: the Tibet AS III array [3], the Argo YJB array [4] at the same site and the MILAGRO detector [5]. Table 2 lists some of the essential parameters and Figure 3 shows the sensitivity as a function of energy in comparison with some other detectors.

Table 2: Comparison of the threshold and sensitivity of current large array detectors

	Height	Coordinates	Area	Threshold	Sensitivity/year
Tibet AS III	4300 m asl	90.5° E, 30.1° N	270x270 m ² , 150x150m ² higher density infill	≈ 3 TeV	≈ 1 Crab
ARGO YBJ	4300 m asl	90.5° E, 30.1° N	10000m ² after completion	0.5-1 TeV	≈ 0.3 Crab
Milagro	2630 m asl		60 x 80 m ²	≈ 2 TeV	≈ 0.5 Crab

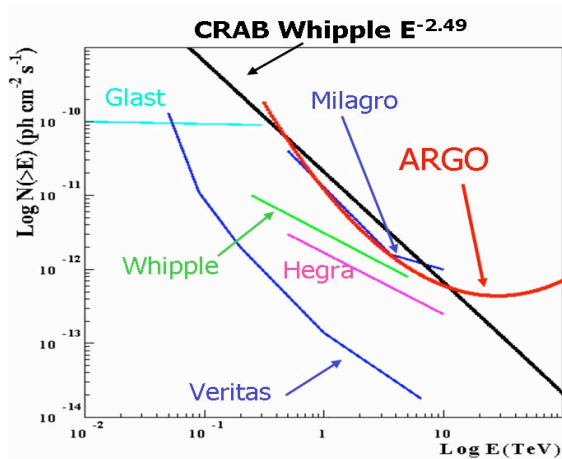


Figure 3. Sensitivity of some γ -ray detectors.

The Tibet AS array resembles most closely the classical scintillator array detector and has been modified during the past years. Originally it was an array of rather coarse grid of scintillation counters with a very low active detector fraction. Successively the array was modified by reducing the spacing between counters and increasing their numbers as well as the overall size. The first discovery, besides the shadowing of CRs of the moon and sun (a very important measurement for the orientation of the array) was the observation of the CRAB nebula with 5.5σ over an observation time of 550 days. Also, evidence for the γ emission from Mkn 501 during a high state in 1997 was reported [6]. The real strength of the instrument is the all-sky

survey potential. Besides the observation of the Crab nebula a number of so-called hot spots, local clusters of particles above the continuum background of charged CRs, e.g., potential signals above 4 but below 5σ have been detected [7].

The Argo detector, located at the same site as the Tibet AS detector, follows the line of a high altitude array with basically 100 % active area coverage by means of resistive plate chambers (RPC) that allow to measure the transit times of individual particles with very high (< 1 nsec) precision. The array is complemented by a layer of lead, acting as a converter for the more frequent low energy secondary γ s, and a second layer of RPCs. The detector is shortly before completion. Initial tests with a smaller section and shorter observation times of the array have not yet resulted in a positive identification of sources [8].

The Milagro detector is currently the most advanced fully active array detector based on a large, rather deep water pond equipped with a rather dense grid of PMTs detecting the Cherenkov light of shower tail particles. The depth of the pond is deep enough to convert also most of the shower tail γ s without stopping the low energy electrons before their detection (a problem with scintillation counters with lead converters). One of the problems of Milagro was its relatively small extension, e.g. most showers were only partially hitting the sensitive area, leading thus often to ambiguous identification. This has been improved by adding outside water pond detectors. A remarkable progress in γ /hadron identification, a notorious problem in tail catcher calorimeters, has been achieved by a new analysis method based on the particle hit pattern in the pond (see contribution to this conference). During this conference a number of new results have been reported, demonstrating the superior power of a fully active detector (see contribution B. Allen, J. Goodman and G. Yodh to this conference) compared to the classical scintillator array detectors.

I would like to briefly mention that besides the array reaching at least partially to below a TeV there exist also arrays with much higher thresholds and a different physics goal, e.g. to study physics linked to the charged CRs. The Kaskade [9] and its follow-up extension Kaskade Grande at Karlsruhe is basically a classical, coarsely sampled scintillator array complemented by muon detectors and a large central hadron calorimeter. The array has a threshold of ≈ 100 TeV, i.e., above all up to now identified sources. A source search [10] gave no positive results. Also the search for diffuse γ s from the galactic plane was negative.

A completely different concept of an array detector is followed by the Tunka collaboration. Tunka [11] and its follow up proposal Tunka 125 consists of an array of large open PMTs observing during dark clear nights Cherenkov light emitted by large showers in the sky. The detector has a superior angular resolution and a very good energy resolution compared even to IACTs due to multiple

sampling of the large diameter Cherenkov light disk. Tunka aims primary for the study of CRs around the knee but the principle allows lowering the threshold close to 1 TeV. The third one, the IceTop [12] detector on the South Pole is again a classical, coarsely sampled array detector following the ice Cherenkov tank concept. The Cherenkov radiators are made from frozen, carefully purified water. IceTop serves mainly for the calibration of IceCube.

In summary, one can conclude that current array detectors of a low threshold just barely see the strongest VHE γ -emitting sources with $\approx 5 \sigma$ /year such as Crab and Mkn 421, 501 and in case of Milagro an extended hotspot around the Cygnus region (see contribution to this conference). The array detectors with higher thresholds see no source signals. This is in stark contrast to results of current IACTs, despite the array's much longer up-time and all sky monitoring ability. The high threshold and the large increase of it as a function of the zenith angle anyhow restrict observations to galactic sources and very low redshift AGNs and GRBs. A look at the future shows that some modified concept or change of detectors could make the array detectors again competitive for special searches.

4. Improvements of current arrays and next generation detectors

The current progress of the Milagro detector show the directions for the future. Classical array detectors have a rather modest γ/h separation. The new analysis technique of Milagro nevertheless shows that progress can be made by analyzing the hit pattern in a fully active detector leading in this case to an improved quality factor (Q-factor) for γ/h separation of up to 8, which brings Milagro closer in performance to IACTs. Another must for tailcatcher calorimeters for lowering the threshold is installing them at high altitudes as can be directly concluded from fig. 1. Shower tail particles are spread over a large area. As a consequence many old arrays often were too small to contain the entire shower tail area and thus led to mistakes in energy and angle determination. The only currently proposed new array detector which incorporates better γ/h separation, lower threshold, in part by the conversion of the numerous tail γ s, and a fully active area sufficiently large to contain the full pattern of showers close above threshold is the HAWC project [13], based on the Milagro concept. Besides a larger area and a high site altitude also better technology should improve the pond detectors. For example the use of Tyvek or Teflon foil or dielectric mirror foil VM2000 from 3M should result in better light collection. Water-soluble wavelength shifters [14] can randomize the Cherenkov light and shift a significant part of the UV light to the peak sensitivity of PMTs. Also progress in PMTs is possible to both lower the cost and increase the sensitivity such as so-called Smart PMTs [15], [16] concept. New readout electronics such as low cost, low power GHz F-ADCs based on large switched capacitor arrays will allow to record the signal development with high time resolution and further allow to improve angular resolution and γ/h separation as well as acting in part as delay lines.

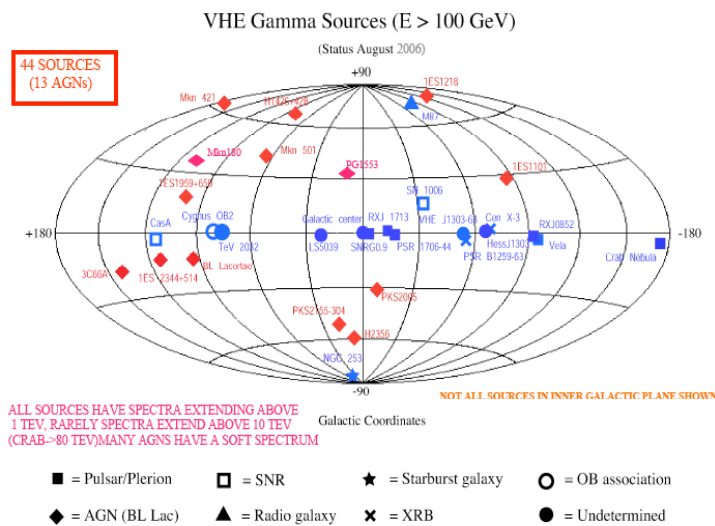
For the time being the MILAGRO/Hawc concept at high altitude seems to be the only viable concept for tailcatcher calorimeters with a sufficiently low threshold and good γ/h separation. If one is willing to accept to give up the 24 h up-time one can build wide angle Cherenkov detectors, such as an improved version of the AIROBICC/TUNKA array of large open PMTs looking directly into the sky (threshold restricted to above 1 TeV) or arrays of medium size IACTs which cover a large section of the sky by pointing each to another small area. These telescope arrays CTA [17], HE-ASTRO [18] are still in the early design phase but promise a low threshold and high γ/h separation, albeit without 24 h up-time.

5. Conclusions

Most of the current discoveries in VHE γ astronomy (see some of the contributions and the review summary to this workshop by F. Krennrich) have been achieved by IACTs because of their superior γ/h separation and lower thresholds. The situation is highlighted by the skymap of γ -sources, figure 4, nearly all of which were discovered in the last 15 years by IACTs. Nevertheless there exists a physics area which cannot be exploited by IACTs and where new high sensitivity, low threshold array detectors can make important contribution to the field:

- Observation of rarely flaring AGNs, which might happen during day-time
- Search for cosmic sources in which dominantly hadronic production of γ s occur and where X-ray satellites are unlikely to give guidance to IACTs
- Observation of large structures (extended sources....)
- Detection of short (<few sec) GRBs. The detection of these sources is, except by accident, excluded for IACTs because of too slow response.

The soon expected opening of the HE/VHE ν window (see the many contributions to this workshop) will require complementary detectors that monitor the γ -sky continuously. Array detectors



can best fulfill this. The conditions for low threshold and high γ/h separation require having large fully active area coverage, better γ/h separation than previous detectors and the most important condition, operating these detectors at high altitude. Currently, only the HAWC project fulfills these requirements and is able to compete with IACTs. New technologies, particularly in photon detection, readout electronics and data processing, might open new possibilities to further improve the array detectors and, in addition, approach the cost goal of 100-200\$/m² area.

Fig. 4. Sky map of VHE γ -emitting cosmic sources (not all shown in the inner galactic plane due to cluttering)

Acknowledgements

I would like to thank my many colleagues from other experiments, who helped me with important details. Also I would like to thank Sybille Rodriguez for helping me to prepare the manuscript.

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