New Generation Atmospheric Cherenkov Detectors

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Abstract

High energy $\gamma$-ray astronomy has been established during the last decade through the launch of the Compton Gamma Ray Observatory (CGRO) and the success of its ground-based counterpart, the imaging atmospheric Cherenkov technique. In the aftermath of their important and surprising scientific results a worldwide effort developing and designing new generation atmospheric Cherenkov detectors is underway. These novel instruments will have higher sensitivity at $E > 250$ GeV, but most importantly, will be able to close the unexplored energy gap between 20 GeV and 250 GeV. Several ground-based detectors are proposed or under construction. Aspects of the techniques used and sensitivity are discussed in this overview paper. The instruments cover largely complementary energy ranges and together are expected to explore the $\gamma$-ray sky between 20 GeV and 100 TeV with unprecedented sensitivity.

Key words: $\gamma$-ray astronomy: GeV - TeV energies – ground-based instruments: atmospheric Cherenkov detectors

1 Introduction

The EGRET detector on-board of CGRO has stimulated the field of high energy astrophysics by the detection of 271 $\gamma$-ray sources (1) in the energy range between 10 MeV - 20 GeV. In parallel, the success of the ground-based imaging atmospheric Cherenkov technique, operating between 250 GeV - 50 TeV, has demonstrated that $\gamma$-ray astronomy can be expanded well beyond GeV energies. A pioneering experiment, using the Whipple Observatory 10 m imaging telescope, achieved the first unequivocal detection of the Crab Nebula (2), a plerion or pulsar-powered synchrotron nebula. More of a surprise was the discovery of TeV emission from a subclass of active galactic nuclei (AGNs), the so-called blazars: Mrk 421 (3), Mrk 501 (4) and 1ES 2344+514 (5). Although
EGRET has reported 66 high-confidence (and 27 low-confidence) blazar identifications with redshifts between \( z = 0.0018 - 2.286 \), the blazars at TeV energies are all nearby with redshifts between \( z = 0.031 - 0.044 \). It is tempting to speculate \(^{[5]}\) that TeV \( \gamma \)-rays are absorbed by the extragalactic IR background when traveling distances comparable to most EGRET blazars. However, whether or not the non-detection of most EGRET blazars at TeV energies can be attributed to their interaction with IR background photons \( (\gamma \gamma \rightarrow e^+e^-) \), or is simply due to a spectral break at the source, remains an open question, because of the lack of data above 20 GeV.

Contrary to earlier predictions \(^{[1]}\) for the IR background density, recent TeV \( \gamma \)-ray observations show that the energy spectra of Mrk 421 and Mrk 501 extend beyond 10 TeV \(^{[8],[9],[10]}\), the highest energies detected from any AGN. This is still consistent with detailed models \(^{[11]}\) for the IR density. Apart from constraining IR background models, the high energy \( \gamma \)-rays from nearby blazars can also provide important data to test \( \gamma \)-ray production models. In particular the possibility of acceleration of hadronic cosmic rays in jets of blazars can be studied. Extending the measurements to 100 TeV and down to 20 GeV could provide the crucial evidence for the understanding of particle acceleration in jets. Also the fact that the \( \gamma \)-ray peak emission occurs at vastly different energies, e.g., at a few GeV for 3C 279 \(^{[12]}\) and at a few hundred GeV for Mrk 501 \(^{[13]}\) (a weak detection by EGRET has been reported just recently \(^{[14]}\)) emphasizes the importance of a big energy coverage in blazar studies. A wide range of energies from 20 GeV up to 100 TeV with a good energy resolution is desirable to study spectral features.

The interest in galactic \( \gamma \)-ray astronomy was ignited by the detection of two additional plerions PSR 1706-44 \(^{[15]}\) and Vela \(^{[16]}\) and even more so, by a detection of a shell-type supernova remnant, SN 1006 \(^{[17]}\) by the CANGAROO telescope. One of the primary motivations for galactic \( \gamma \)-ray astronomy is the understanding of supernova shock acceleration and the origin of the galactic cosmic rays. The search for their most promising acceleration sites, in shell-type supernova remnants \(^{[18]}\), requires a good sensitivity for extended \( \gamma \)-ray emission. Future atmospheric Cherenkov detectors will also address the sensitivity for extended sources like the galactic plane and shell-type supernova remnants.

GeV and TeV \( \gamma \)-ray measurements have caused a wide scientific interest. It is crucial for the understanding of the \( \gamma \)-ray emission processes to close the energy gap between 20 GeV - 250 GeV and to advance the sensitivity between 250 GeV - 100 TeV. The gap between 20 GeV and 250 GeV can be explored with future satellite and ground-based instruments. Both techniques are currently being investigated: the satellite-based GLAST \(^{[20]}\) detector with a relatively small collection area but a wide field of view, and the ground-based atmospheric Cherenkov technique with a small field of view but a large collection.
The energies above 250 GeV will remain the domain of the ground-based detectors. In this overview of atmospheric Cherenkov detectors, the detection principle and their anticipated sensitivity, energy range and angular resolution are discussed. In Section 2 important design considerations for atmospheric Cherenkov detectors are briefly outlined. In Section 3 the individual detectors are described. Section 4 gives a summary of the anticipated performance of the various instruments emphasizing their individual strengths.

2 Design Considerations

The design of a new instrument is driven by science. From the previous section it is evident that the need for a wide range in energy (20 GeV - 100 TeV), wide field-of-view and spectroscopic capabilities puts many requirements on future detectors. The detection principle of \( \gamma \)-rays above 20 GeV from the ground is based on the measurement of Cherenkov light from the electromagnetic atmospheric cascade initiated by the \( \gamma \)-ray primary. The Cherenkov light emitted from the secondary e\(^\pm\) over a range of altitudes (6 - 20 km atmospheric height) is focused onto an area of 200 - 300 m diameter at ground defining the light pool. The collection area, the area from which a shower can be detected, is in the order of 70,000 m\(^2\), although the area also depends on the energy and detailed detector design. The intrinsically large collection area of atmospheric Cherenkov detectors (order of \(10^5\) larger than EGRET’s collection area) would ideally extend the sensitivity above 20 GeV, where EGRET’s measurements are limited by statistics. The large collection area also provides the means for the detection of low fluxes in the 1 TeV - 100 TeV regime with a good sensitivity. In particular large zenith angle observations, which provide an even larger collection area (several 100,000 m\(^2\)), is efficient for the detection of the highest energies above 10 TeV (21, 22, 23). The following issues need to be addressed by future detectors to reach the objectives outlined in the previous section: a low energy threshold of 20 GeV, improved sensitivity between 200 GeV - 100 TeV, high angular resolution (few arcminutes) and good energy resolution (10%).

2.1 Low Energy Threshold

The detection of low energy \( \gamma \)-ray air showers requires triggering on faint Cherenkov light flashes, e.g., 2.5 photons per m\(^2\) from a 50 GeV \( \gamma \)-ray shower\(^1\). A limitation arises from the night sky background light (NSB \(\approx 2 - 4 \times\)).

\(^1\) This value comes from Paré 1996 and is valid for the Thémis site. The absolute value depends on the altitude and atmospheric conditions at the observational site.
$10^{12}$ photons/m²/s/sr) through its fluctuations $\sqrt{\text{NSB}}$: however, since the Cherenkov pulses are extremely short (5 - 10 ns), the NSB can be greatly reduced (e.g., 0.8 -1.6 photons/m² within 5 ns for a photosensitive detector with 0.6° sensitive diameter[7]). Air showers can only be detected if the Cherenkov signal exceeds several times $\sqrt{\text{NSB}}$. This can be quantified by the signal to noise ratio, defined as the number of Cherenkov photons over the night sky fluctuation. A low energy threshold detector requires the optimization of the signal to noise ratio, e.g., by minimizing the solid angle acceptance $\Omega$ of the triggering photodetectors or by shortening the coincidence time window for the Cherenkov pulses in different photodetectors effectively reducing the $\sqrt{\text{NSB}}$ contribution. For imaging telescopes the solid angle acceptance covered by the minimum required photodetectors (typically photomultipliers) should be comparable to the $\gamma$-ray image size scale. The time window $\tau$ should be close to the intrinsic pulse width of the Cherenkov flash.

In order to lower the energy threshold of atmospheric Cherenkov detectors (presently $E > 250$ GeV) to 50 GeV (20 GeV), the number of Cherenkov photons collected has to be substantially increased, e.g. through increasing the mirror area $A_{\text{mirror}}$. The energy threshold scales as $E_{\text{thres}} \propto \sqrt{\text{NSB}} \Omega \tau / A_{\text{mirror}}$.

Simple extrapolation from existing instruments, for example the Whipple 10 m telescope which operates at a high signal to noise ratio, suggests a mirror area of $\sim 1800$ m² and $\sim 11,700$ m² to reach 50 GeV and 20 GeV respectively. However, it is important to notice, that the overall quantum efficiency of existing detectors (the convolution of mirror reflectivity and photomultiplier quantum efficiency) does not exceed $\approx 10\%$[24], dominantly hampered by the low quantum efficiency of photomultiplier tubes. Improving the light collection efficiency also lowers the energy threshold.

Future atmospheric Cherenkov detectors described in Section 3 use various means to achieve a lower energy threshold. Arrays of 10 m imaging telescopes, proposed by the VERITAS [25] and HESS [26] collaboration, aiming for an energy threshold of $\sim 100$ GeV, are based on a moderate increase of mirror area, combined with fast electronics and fine pixellation imaging cameras. The MAGIC [27] collaboration proposes a single 17 m imaging telescope aiming for a low energy threshold through a modestly increased mirror area together with high quantum efficiency phototubes. A dramatic increase of mirror area

\[ \text{The minimum solid angle acceptance required for an atmospheric Cherenkov detector is $\approx 0.6^\circ$ to cover the angular extend over which the Cherenkov light from a sub-TeV $\gamma$-ray shower from a point source occurs determined by its intrinsic angular size and shower height fluctuations. However, the light distribution of a $\gamma$-ray shower image is elliptical and peaked and can be described by its width and length with a scale of $0.15^\circ \times 0.3^\circ$. With imaging telescopes the aperture for the triggering pixels can be reduced through the use of a fine pixellation camera, effectively reducing the NSB.} \]
is currently explored by the STACEE \((28)\) and CELESTE \((29)\) collaborations, where 48 - 160 heliostats of solar power plants give a gigantic mirror area for detection of $\gamma$-rays down to $\approx 30$ GeV.

2.2 Sensitivity, Angular and Energy Resolution

The rejection of much more numerous cosmic-ray induced showers has been pivotal in establishing the sensitivity of ground-based TeV astronomy \((2)\). In contrast to satellite instruments, which utilize anti-coincidence scintillator shields inhibiting the detector from triggering on charged cosmic-ray particles, ground-based instruments rely mostly on background rejection in off-line analysis. The imaging technique has provided an efficient means to separate $\gamma$-ray from hadronic initiated showers which can be expressed by a quality factor $Q$ defined as $Q = \varepsilon / \sqrt{\kappa}$ with $\varepsilon = \text{efficiency for } \gamma$-rays and $\kappa = \text{efficiency for cosmic-ray events.}$ Because the detection of $\gamma$-rays is background dominated ($\sim 10^3$ more cosmic rays than $\gamma$-rays), the sensitivity of any atmospheric Cherenkov detector depends critically on its background rejection capability.

The measurement of the arrival direction of $\gamma$-rays depends on the detection technique: an arrival time measurement of the wavefront of Cherenkov photons (as used in STACEE and CELESTE) or by the analysis of the shower image orientation in imaging telescopes (VERITAS, HESS and MAGIC). A good angular resolution is particularly important for point-source sensitivity at energies below 100 GeV, where isotropically arriving cosmic electrons constitute an additional, non-hadronic background, which cannot be rejected through $\gamma$/hadron separation. The angular resolution naturally improves with the $\gamma$-ray primary energy from $0.1^\circ$ below 100 GeV up to the $0.02^\circ$ range at TeV energies.

The energy resolution is important for extracting the physics of the $\gamma$-ray source. For example the sharp spectral breaks in pulsars as suggested by the polar cap model \((30)\) and generally the measurement of the spectral breaks of most EGRET sources between 20 GeV and 200 GeV provides motivation for an energy resolution in the range of 10%.

3 However, at the hardware trigger level some background is rejected, because at $E \approx 100$ GeV ($300$ GeV) a $\gamma$-ray induced shower produces 10 times (4 times) more light than a proton induced shower of the same energy. Also, the field-of-view determines the background level. Therefore, a comparison of instruments should include both, the off-line and the hardware rejection capability.
3 Future Projects

3.1 Imaging Telescopes

The imaging technique uses optical reflectors (e.g. Whipple 10 m telescope) with a tessellated mirror structure and a matrix of fast photomultipliers in the focal plane. With this configuration an image of the Cherenkov light of an air shower is measured and analyzed. Weekes et al. [2] have demonstrated that the analysis of image shape and orientation is very efficient in distinguishing γ-ray from cosmic-ray initiated air showers. A Q-factor of $\approx 10$ (99.7% of cosmic rays are rejected while keeping 60% γ-rays) with the Whipple 10 m telescope has been pivotal in establishing the imaging technique, which is to date the only technique which has detected γ-ray sources above 250 GeV at a level of $\geq 10\sigma$. The Crab Nebula is detected at a rate of 2 γ-rays per minute with a sensitivity of about $7\sigma$ per hour. Based on this success, two different concepts have been proposed to increase the sensitivity further: the development of an optimized single large telescope (MAGIC) and stereoscopic imaging using multiple telescopes (VERITAS and HESS).

3.1.1 Single Telescope Imaging: MAGIC

The potential of improving the single telescope imaging method has been recognized by several groups: CAT, MAGIC and the Whipple collaboration. Although the CAT imaging telescope employs a relatively small 18 m² mirror (75 m² for the Whipple 10 m) an energy threshold of 200 GeV has been reached [31]. This is due to fast electronics and a fine pixellation camera (0.12° vs. 0.25° for the Whipple 10 m) optimizing the signal to noise ratio at the trigger level. The combination of a 10 m telescope with a pixellation of 0.12° is currently pursued by the Whipple collaboration (GRANITE III) by upgrading the 10 m telescope [32]. An energy threshold of 120 GeV is anticipated.

To push this strategy further, the MAGIC collaboration pursues the design of a 17 m diameter telescope. The concept is based on increasing the mirror area, a better quantum efficiency (45% GaAsP photocathode) of the photon detection devices and fast speed electronics. Estimates given by the MAGIC collaboration quote an energy threshold of 30 - 40 GeV using standard photomultipliers and 15 GeV using photodetectors with GaAsP photocathodes [27]. Simulations by the MAGIC group show, that 20 GeV γ-ray showers produce images which contain good information about the arrival direction suggesting an angular resolution of 0.2° near threshold[4], and a good background

4 Note that the angular resolution is a function of the primary energy and improves
rejection\(^5\) with a Q-factor of 6. An energy resolution of 50% at the threshold energy and 20% at 100 GeV is quoted.

### 3.1.2 Stereoscopic Imaging: VERITAS and HESS

A logical extension of the single telescope imaging technique is the stereoscopic detection of air showers with multiple instruments which has been first demonstrated by Grindlay \(^\text{33}\). The detection of a γ-ray signal with multiple imaging telescopes was demonstrated by Daum et al. \(^\text{34}\) and Krennrich et al. \(^\text{35}\). Impressive results have come from the HEGRA telescope array (4 telescopes of 8.5 m\(^2\) mirror area each) using relatively small reflectors and a pixellation of 0.25°, showing a good angular resolution and excellent background rejection at 1 TeV \(^\text{36}\). Two next generation multi-telescope projects are under development; the VERITAS array (7 × 10 m telescopes) in the northern hemisphere (Arizona) and the HESS project (16 × 10 m telescopes) in the southern hemisphere (Namibia). The major objective of those multi-telescope installations is the stereoscopic detection of γ-ray sources above 100 GeV with a high sensitivity, angular resolution and energy resolution \(^\text{37; 38}\).

The multi-telescope imaging technique is based on the stereoscopic view of γ-ray showers (Figure 1, 2). This provides an angular resolution of 0.08° at 100 GeV and 0.02° for the highest energies for a VERITAS type detector \(^\text{39}\), which by itself improves the background suppression of the cosmic-ray induced showers in comparison to a single telescope. In addition, the image shapes of air showers can be better constrained with several telescopes and be reconstructed in 3-dimensional space providing a measurement of the height of shower maximum, shower impact point on the ground (Figure 2) and the light density at different locations within the Cherenkov light pool. As a result, the γ-ray energy \(^\text{40}\) can be better measured with a resolution of 13% - 18% (corresponding to 10 TeV and 100 GeV). Also the Q-factor improves through a better classification of γ-ray, cosmic-ray or muon images and excellent angular resolution\(^6\). Also, the collection area for the stereoscopic operation of a 7-telescope array requiring a 3-telescope coincidence is increased to 200,000 m\(^2\). Monte Carlo simulations suggest that the point-source sensitivity of the VERITAS array, e.g., at 300 GeV \(^\text{39}\), is a factor of 10 better than with the currently operating Whipple 10 m telescope.

The energy threshold (analysis threshold) of arrays can be lower than for an individual telescope. First, the rejection of local muons (a muon can be detected

\(^5\) Cosmic-ray background from hadrons, muons and electrons has been considered.

\(^6\) Note for a point source the background rejection is due to two different factors, the angular resolution and the distinction of γ-rays from hadronic showers and single muons.
up to 80 m distant from telescope) through an array trigger will be important at γ-ray energies below 300 GeV, where they constitute a major background. Remaining muons falling between the telescopes can be rejected by their parallactic displacement\(^7\). Lastly, faint Cherenkov flashes (barely triggering) do not produce a well defined image shape and hence not much information about the nature of the primary is available. Those images are usually rejected in the single telescope analysis. However, using the stereoscopic view\(^{11, 12}\) γ-ray showers differ from hadronic showers: images from hadronic primaries show a more irregular parallactic displacement than γ-ray induced showers. This method can be used to provide hadronic background rejection at energies close to the trigger threshold of telescope arrays. For VERITAS a trigger and analysis threshold of 50 GeV seems possible using stereoscopic reconstruction methods, and the limit arises mostly from the night sky background fluctuations.

### 3.2 Light Pool Sampling with Heliostats

The potential of utilizing solar power plants for γ-ray astronomy has been recognized\(^{13}\), because mirror areas of several thousand square meters provide the necessary signal to noise ratio to trigger on \(E > 20 - 300\) GeV γ-ray primaries. The exploration of the lowest energies \(E \approx 20\) GeV with a low cost device is the primary objective of the STACEE, CELESTE and GRAAL\(^{14}\) projects.

The principle of detecting γ-rays with heliostats is shown in Figure 3. The Cherenkov light from an extensive air shower is collected with steerable mirrors and reflected onto a stationary secondary mirror located on the central tower. Because the secondary mirror forms an image of the locations of the heliostats it projects the light from each individual heliostat onto a different position in the focal plane. Photomultipliers are used to detect and sample the light distribution. Due to the different times of flight between different heliostats and the secondary mirror it is necessary to delay the signals with respect to each other and combine them afterwards into one trigger. By forming an analog sum of the signals between several phototubes, the total amount of light collected by all mirrors can be combined almost as if it were detected by a single large mirror\(^8\), therefore providing a low energy threshold. Because of the diameter of the Cherenkov light-pool of γ-ray induced showers at 20 GeV (200 m diameter), the number of heliostats which participate in the trigger have to be limited to mirrors which fall into an area of that size.

\(^7\) As opposed to distant γ-ray showers, local muons show a parallactic offset when comparing images in different telescopes.

\(^8\) Alternatively, they can be combined in a digital sum after they have individually passed a discriminator.
The Cherenkov light distribution is sampled at different positions on the ground. This provides information about the Cherenkov light intensity as a function of the position within the light pool. Hadronic showers show more irregular azimuthal variations in the light density within the light pool than γ-ray showers, and this property can be utilized to reject hadronic cosmic-ray showers.

The arrival direction is somewhat preset by a fairly narrow field of view or solid angle acceptance of the configuration (angular extend 1.2°)\(^9\). The arrival direction can be measured by deriving the orientation of the shower wavefront from the delays between the signals from the different heliostats. The arrival direction reconstruction also requires information about the shower core location which can be achieved by sampling the light density on the ground (45) providing an angular resolution of 0.2° with 40 heliostats (CELESTE). First light by the CELESTE collaboration has resulted in a tentative detection of the Crab Nebula at an analysis threshold of 80 GeV (46).

4 Discussion

The different techniques to detect γ-rays from the ground are largely complementary as emphasized in Figure 4. The lowest energies are explored by solar power plants starting at 20 GeV with a sensitivity for point sources. Those instruments will operate up to a few hundred GeV where their narrow aperture limits the detection of higher energy γ-rays. The MAGIC project targets a 15 - 40 GeV energy threshold exploring the imaging technique at the lowest energies. Because of its 2.5° - 3.5° field of view, MAGIC could also provide a sensitivity for extended sources and γ-ray burst counterpart searches. At higher energies of E > 100 GeV (possibly 50 GeV), VERITAS and HESS can detect γ-rays over a big dynamic range of up to 100 TeV, whereas their primary sensitivity is between 100 GeV - 10 TeV. The high angular resolution and strong background suppression provides excellent sensitivity in the order of a few milli-Crab. Also, the combined field-of-view of VERITAS (or HESS) can create maps of extended regions in the sky covering 10° in diameter with a single exposure. An all-sky survey of the TeV sky will be carried out with MILAGRO (47), also providing potentially important information where to point atmospheric Cherenkov detectors.

From Figure 4 it becomes clear that the 20 - 200 GeV window will be opened up for high energy γ-ray astronomy by the alliance of space-based (GLAST) and ground-based Cherenkov detectors.

\(^9\) The solid angle acceptance of individual heliostats is ≈ 0.7°
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Fig. 1. Schematic view of a reconstruction technique which combines images from different telescopes in a 'common' focal plane viewing part of the sky. The scale is in degrees and the simulated images have been recorded from 7 different telescopes. The intersection of the image axes measures the arrival direction of the $\gamma$-ray primary (Courtesy of G.H. Sembroski and M. Kertzman).

Fig. 2. Schematic view of a reconstruction technique which combines images from different telescopes to derive the location of the shower core (where the shower axis actually intersects with the ground) for a 300 GeV $\gamma$-ray shower. Figure shows 7 circles representing the cameras of the 7 telescopes, which are located in a coordinate system of the VERITAS telescope array, where the distance between telescopes is $\approx 85$ m. The individual focal-plane also shows the light content in individual pixels (Courtesy of G.H. Sembroski and M. Kertzman).
Fig. 3. The principle of the detection of Cherenkov light with an array of heliostats of a solar power plant is shown (STACEE). Heliostat mirrors reflect some Cherenkov light onto a secondary mirror of the solar tower where it is focused onto an array of photomultipliers (Courtesy of R.A. Ong).

Fig. 4. The sensitivity of various instruments at GeV to TeV energies. The values have been adopted from the following sources: VERITAS [31], MAGIC [27], GLAST [20] and Whipple [32].
