Gamma ray astronomy with atmospheric Cherenkov telescopes: the future

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New Journal of Physics 11 (2009) 115008 (24pp)
Received 29 May 2009
Published 10 November 2009
Online at http://www.njp.org/
doi:10.1088/1367-2630/11/11/115008

Abstract. Atmospheric Cherenkov telescopes have been key to the recent discoveries in teraelectronvolt (TeV) $\gamma$-ray astronomy. The detection of TeV $\gamma$ rays from more than 90 galactic and extragalactic sources provides a wealth of data for probing physical phenomena that pertain to some of the big questions in astrophysics. These include the understanding of the origin of cosmic rays, unveiling the connection between relativistic jets and black holes, shedding light on dark matter and its relation to supersymmetric particles and estimating the brightness of cosmological diffuse radiation fields in the optical/infrared waveband. While these recent advances were made with instruments designed in the 1990s, the present paper is concerned with a next generation of imaging atmospheric Cherenkov telescopes (IACTs) that are currently in the conceptual planning stage. We discuss the basic ideas, the required technology and expected performance of a $\geq 1$ square-kilometer array, which is poised to yield the most dramatic step yet to come in TeV astronomy.
1. Introduction

Imaging atmospheric Cherenkov telescopes (IACTs) provide the most powerful tool for probing the high-energy universe in the teraelectronvolt (TeV) regime and are founded on pioneering advances that were made in the last two decades. The IACT technique was first successfully implemented in the Whipple 10 m γ-ray telescope and image analysis, where a single instrument led to a tenfold improvement in flux sensitivity over any previous installations [1], and opened a window to galactic and extragalactic TeV astronomy [2]. Another tenfold improvement in sensitivity was made in the last 5 years through stereoscopic imaging with arrays of large-size (12 m diameter) telescopes, namely the HESS [3] and the VERITAS instruments [4]. In addition, the combination of a very large mirror and fast timing is used in the 17 m MAGIC telescope [5], which has also demonstrated a complementary approach to improving sensitivity. A worldwide community has established a catalog of more than 90 TeV sources [6, 7] of a wide range of classes, while IACTs provide unprecedented astronomical capabilities at TeV energies: resolved images of some galactic sources, the measurement of flux variations as short as 200 s, and measurement of energy spectra up to 70 TeV. The IACT technique already provides the best angular resolution (0.1°) of any astronomical technique above 0.1 MeV and has the potential for dramatic improvements. The recent revolution in TeV astronomy was enabled by a tenfold increase in flux sensitivity, while the capital investment for instrumentation increased a factor of 10 compared with previous telescopes. Further improvements are possible and would allow flux sensitivity at the 1 mCrab level (10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}). These advances are likely to use new technologies that have recently become available.

In the following (section 2), I proceed to give a brief discussion of the science requirements that are drivers for the key specifications of future instruments. In section 3, the large array concept and its principle design considerations are presented, including the fundamental limitations associated with the detection of Cherenkov light from air showers. In section 4,
I will discuss the most promising technologies for a future IACT system, including new optical designs and modular camera concepts and related research and development efforts that may be critical for the next generation of IACTs. Finally, in section 5, I briefly refer to specific array concepts that are being considered and are currently at the conceptual design stage.

2. Science requirements and key specifications

Future IACTs will become an important follow-up to the all-sky survey at $E \geq 0.1\text{GeV}$ provided by the Fermi space telescope [8]. The excellent point source sensitivity and angular resolution of the IACT technique already enable in some cases symbiotic Fermi/IACT studies with current instruments [9]. However, a 5–10 year Fermi exposure of our galaxy with well over $10^3$ (see also review by R Johnson and R Mukherjee in this volume) objects will require a sensitive follow-up with a future IACT to extend statistical studies of source classes well into the TeV regime, thereby providing a combined coverage of six orders of magnitude in energy. This is particularly promising since IACTs allow detailed morphological and spectral studies well into the tens of TeV regime. This is critical for probing particle acceleration and the identification of particle populations in perhaps the most interesting regime, where electrons and protons distinguish themselves through their vastly different synchrotron cooling properties and may help break the degeneracy of leptonic and hadronic emission models.

In the following, I provide a brief science motivation for the most important instrument parameters of future IACTs. For more details on the scientific results achieved with current generation instruments see the review by J Hinton [10]. Owing to the fact that TeV astronomy provides information on a broad range of astrophysical objects, it is important to identify common instrument parameters that are critical for the individual science topics. A brief discussion of the science is followed by a summary and table (table 1) describing improvements, necessary for future major scientific breakthroughs in non-accelerator high-energy physics and TeV astronomy.

2.1. Galactic astrophysics

Our galaxy harbors particle accelerators that exceed the energies reached by any man-made machine, including the large hadron collider [11], by several orders of magnitude. A key science goal of TeV astronomy with $\gamma$ rays and neutrinos [12] is to understand the origin of cosmic rays [13, 14] and the nature of their sources [15, 16]. Cosmic rays should not escape their sources without leaving a trace of $\gamma$ rays through the interaction with molecular gas in the vicinity of cosmic accelerators and subsequent neutral pion ($\pi^0 \rightarrow \gamma\gamma$) and charged pion ($\pi^\pm \rightarrow \cdots + \nu$) production. Identification of $\gamma$-ray sources and mapping their angular extent are most promising, e.g. for testing the paradigm that the remnants of supernova explosions are responsible for producing protons and other hadrons up to a few times $10^{15}\text{eV}$ (PeV) [17, 18]. Angular-resolved studies of individual sources [19]–[21] trace the spatial distribution of particles and are key to mapping the physical conditions in the $\gamma$-ray emission region. While a hadronic origin generally requires $\gamma$ rays and molecular gas to be co-spatial, TeV $\gamma$ rays could also be produced by relativistic electrons via inverse Compton scattering of ambient photons, e.g. the cosmic microwave background (CMB). In this case, a spatial correlation between x-ray emission and TeV emission is expected due to the dual role of electrons producing synchrotron (x-ray) and inverse Compton (TeV) emissions. Angular-resolved spectroscopy of TeV photons
Table 1. Mapping of Instrument Capability Improvements and Science Topics. The numbers in brackets refer to the current source counts at TeV energies [6]. The symbol ‘+’ means important, ‘++’ means critical and the non-assignment of a symbol means that it is not a high priority.

| Science Object | $S_{\leq 2\text{ TeV}}^a$ | $S_{\geq 2\text{ TeV}}^a$ | Angular resolution$^b$ | F.O.V. | Area |
|----------------|-----------------|-----------------|-------------------|--------|------|
| Cosmic SNRs (7) | ++              | ++              | ++                | ++     | ++   |
| ray Dark accelerators (28) | ++              | ++              | +                 | +      |
| origin Star clusters (1) | ++              | ++              | +                 | +      |
| Galactic center (1) | ++              | ++              | +                 | +      |
| Starburst galaxies (1) | ++              | +               |                   | +      |
| Galaxy clusters (0) | ++              | ++              |                   | +      |
| Compact Pulsars (1) | ++              | ++              |                   | +      |
| objects Pulsar wind nebulae (10) | +               | ++              | ++                | +      |
| Binary systems (3) | ++              | ++              |                   | +      |
| Rel. jets Blazars (24) | ++              | ++              | +                 | +      |
| Radio galaxies (2) | ++              | ++              |                   | +      |
| GRBs (0) | ++              | +               | ++                | +      |
| Microquasars (?) | ++              | ++              |                   | +      |
| Dark Dwarf galaxies (0) | ++              | ++              |                   | +      |
| matter Microhalos (0) | ++              | ++              | ++                | +      |
| Intermed. M. B.H.s (0) | ++              | ++              | ++                | +      |
| EBL$^c$ | +               | ++              |                   | +      |
| B-Fields$^d$ | ++              | ++              |                   | +      |
| Q. G.$^e$ | ++              | ++              |                   | +      |

$^a$ Fermi covers the energy regime up to a few 100 GeV; however, due to its small area, the spectral coverage in the tens of GeV regime and above is photon limited. The coverage of this energy regime by IACTs with a large collection area is particularly relevant for time-variable phenomena and a search for spectral features that might occur in that overlap regime.

$^b$ Here, we refer to the benefits that angular resolution provides for yielding better astrophysical information. Better angular resolution also helps to improve sensitivity by better cosmic-ray background rejection and is included in the two columns to the left.

$^c$ Here, we refer to the extragalactic background light (EBL) with emphasis on the near-IR and mid-IR wavebands.

$^d$ B-fields refer to intergalactic magnetic fields that could result in delayed GeV γ rays from a blazar flare due to the development of an electromagnetic cascade in extragalactic space.

$^e$ Q. G. refers to tests of quantum gravity (Q. G.) theories that imply Lorentz invariance violation via an energy-dependent speed of light at energies close to the Planck energy.

needs to approximately match the fine structure of shells that have been unveiled at the sub-arcminute scale with X-ray studies [22] and would be the most powerful tool to identify electron populations [23] and distinguish hadronic from leptonic origin.

A larger collection area is necessary to make use of a better angular resolution to provide sufficient photon statistics. An order of magnitude increase in collection area paired with a factor of 2–3 better angular resolution would be a major step forward towards resolving the non-thermal emission regions in our galaxy and identifying cosmic accelerators. A ten times increase in the coverage of this energy regime by IACTs with a large collection area is particularly relevant for time-variable phenomena and a search for spectral features that might occur in that overlap regime.
better sensitivity is required for broad studies with several hundred galactic TeV sources [24] and is key for attributing the cosmic accelerator phenomenon to a specific class/classes of astrophysical objects. Furthermore, in order to map supernova remnants of a large angular size (angular size $\sim$ few degrees), e.g. Vela Junior [19] and to detect regions where multiple supernovae have occurred, a larger field of view than currently employed by IACTs is desirable. Additional evidence for extended sources of several degrees across was also provided by the Milagro experiment [25].

Other particle accelerators in our galaxy include compact objects such as pulsars [26]–[28], pulsar wind nebulae [29, 30], pulsar wind binaries [31] and possibly microquasars [4, 32, 33]. The $\gamma$-ray detection of rapidly spinning neutron stars is currently the domain of space-based telescopes (Fermi, AGILE). Nevertheless, the IACT technique offers unique capabilities, as was demonstrated by a recent detection of the Crab pulsar above 25 GeV [26]. The inherently large collection area of IACTs could be used to provide large photon statistics for mapping the cut-offs of pulsed emission, thereby probing particle acceleration in pulsar magnetospheres. This provides a key motivation to improve the sensitivity of IACTs in the 20–100 GeV regime. TeV $\gamma$ rays also probe the interaction of the relativistic wind from a pulsar with its surrounding interstellar medium or a massive binary star, as found in high-mass x-ray binaries. Particle acceleration in shocks do potentially generate PeV electrons that produce TeV emission via inverse Compton scattering of ambient radiation fields. Given the angular extent of some of these pulsar wind nebula [30, 36], an angular resolution improvement of a factor of a few would allow mapping of the particle distribution and diffusion processes in many objects.

The understanding of the origin of cosmic TeV electrons is also critical for the interpretation of possible dark matter signatures that might contribute to the locally measured cosmic-ray electron spectrum. A recent report of an excess around 600 GeV in the ATIC balloon experiment [37] could be interpreted as a signature for dark matter; however, the result is not confirmed by data from Fermi [38]. IACTs also measure the electron spectrum up to multi-TeV energies; however, they provide high statistics [39] using a complementary technique. A putative excess could be interpreted as a dark matter self-annihilation signature, or could also arise from a relatively nearby pulsar [40, 41] or have its origin in a nearby supernova remnant [42, 43] or microquasar [44] and highlights the importance of understanding astrophysical cosmic-ray backgrounds.

Serendipity and discovery of the unexpected is the hallmark of a new field in astronomy and astrophysics, and one of the most intriguing phenomena found in the TeV regime is a population of sources that have no identified counterpart in other wavebands [45]. However, counterpart searches for some of these are underway [34, 35]. These ‘TeV bright’ and otherwise ‘dark’ objects shed light on components of the galaxy that remain unaccounted for by other astronomical techniques, and TeV astronomy may help to complete the energy budget of our own galaxy. Extended population studies with sufficient statistics and identification with other components are key to understanding the role of relativistic particles in our galaxy. An order of magnitude of sensitivity improvement would provide the statistics for population studies for understanding the collective contribution of individual source classes to galactic cosmic rays.

A deep survey of the galactic plane at TeV energies with an order of magnitude better sensitivity and a factor of a few better angular resolution over the existing survey by HESS [46, 47], would extend the Fermi sky survey to tens of TeV and would likely reveal several hundred galactic TeV sources [24], which would allow one to separate their contribution from the galactic diffuse emission. Such future IACT would allow for broad population studies.
and detailed probes of individual sources and might also provide the critical data for solving
the century old question of the origin of cosmic rays, a component of the interstellar medium
that fills our galaxy with an energy density comparable (factor of a few) with that contained in
the galactic magnetic field. The TeV extension of the Fermi sky survey [8] may be critical to
identifying the dominant contributors to the cosmic-ray phenomenon.

2.2. Extragalactic astrophysics

The relativistic jets of active galaxies (AGNs), when pointed towards the observer (blazar),
exhibit flares and temporarily become the brightest TeV γ-ray sources in the sky. More than two
dozen active galaxies have been detected at TeV energies [6], with redshifts between 0.0018 and
0.536. Detailed studies of the time structure and spectral energy distribution allow one to probe
γ-ray emission models (for review and further references see [50]), the acceleration mechanism
and ultimately the relation between the relativistic jet and the supermassive black hole (SMBH)
powering the jet [48]. Flux variations may be attributable to the smallest scale of the system
and are expected to be of the order of the light-crossing time of the Schwarzschild radius of the
SMBH. A recent concerted international observing campaign (HESS, MAGIC, VERITAS and
the VLBA 43 GHz M87 monitoring team) of the nearby (z = 0.004) radio galaxy M87 resulted
in the detection of a TeV flare [49] simultaneous to high-resolution radio imaging observations
(VLBA) and indicate that the TeV emission region originates within ∼50 Schwarzschild radii
of the SMBH. Time-resolved studies of the spectral energy distribution of AGNs are the key to
understanding the central ‘machine’ that is powering the relativistic jet. While flaring timescales
as short as 200 s have already been detected for the brightest flares [51, 52], much shorter
timescales and thereby even smaller emission regions can be probed [53]. An order of magnitude
better sensitivity through a larger collection area could allow one to probe timescales as short
as 10 s, which corresponds to the order of the Schwarzschild radius of a 10^8 M_{solar} SMBH,
assuming the emission region is moving with a Doppler factor of 100.

TeV photons can also be used to probe the diffuse cosmological radiation fields on
intergalactic distance scales through absorption via γ_{TeV} + γ_{IR} → e^+ + e^- [54]. The energy
spectra of blazars should contain an imprint of the energy-dependent opacity from propagation
through the diffuse cosmic optical to infrared (IR) background, the latter being very difficult
to measure directly [55]. TeV spectra from the sub-100 GeV to 10 TeV regime can be used to measure/constrain these radiation fields (for recent overview see [56] and references therein) providing important information about the star and galaxy formation history of our
universe. Spectral measurements are currently still limited by photon statistics in the multi-TeV
regime [57, 58], most critical for determining the primordial radiation field in the near-to-mid
IR. Both increasing the collection area and the extension to sub-100 GeV energies are most
critical for identifying absorption features.

Gamma-ray bursts (GRBs) will remain a key target for next generation TeV telescopes.
Delayed γ-ray emission from GRBs detected by EGRET and recently confirmed by Fermi,
make GRBs promising targets for future Cherenkov telescopes. Most recently, Fermi observed
a GRB at a redshift z ∼ 4.4 [59] and detected a 13 GeV photon 16 s after the instrument
was triggered. This corresponds to 70 GeV photon energy before redshift by the expansion of
the universe. For effective follow-up observations, a rapidly slewing and wide field of view
instrument is necessary since the fastest burst notifications from satellite-based instruments
provide limited angular precision of 10° (Fermi GBM). A low-energy threshold well below
100 GeV is critical for the detection of distant GRBs ($z > 1$) as the opacity to the optical to near-IR cosmological background radiation becomes a serious obstacle to higher energy photons.

Finally, the recent report of the discovery of TeV emission from the first starburst galaxy M82 [60] allows one to probe the connection between the collective star formation activity and associated supernova activity and cosmic-ray acceleration. While current generation instruments such as VERITAS have demonstrated the sensitivity to detect a weak signal from M82, detailed studies and precision energy spectra will require a better sensitivity and larger collection area.

2.3. Astroparticle physics

The indirect detection of dark matter may be possible via the identification of annihilation products ($\gamma$ rays) from weakly interacting massive particles, namely the neutralino, a prime dark matter candidate [61]. Most promising for $\gamma$-ray detection are regions with enhanced dark matter density, e.g. the cores of galaxies like our Milky Way [62]–[64], nearby dwarf galaxies [65] and nearby microhalos around intermediate mass black holes. The key to improving the chances for a positive detection are to maximize flux sensitivity over an energy regime of 40 GeV to tens of TeV. Prospects of detecting a unique signature via a $\gamma$-ray line from dark matter annihilation and/or a universal $\gamma$-ray spectrum are the key motivation for improving the energy resolution with next-generation telescopes. While Fermi will provide excellent sensitivity at energies below 100 GeV through a many year all-sky survey, a future IACT could provide complementary coverage with superior point-source sensitivity at energies above a few tens of GeV, while providing a unique coverage for a universal emission spectrum and a putative annihilation peak that could be identified with high statistics at energies above 100 GeV.

2.4. Instrument requirements—science goals

The key improvements of instrument parameters over existing IACTs can be summarized as follows:

- One of the most prominent features of the IACT technique is its inherently large collection area, determined by the size over which the Cherenkov light is spread at observatory level. The scale of the collection area corresponds to the size of a few times that of a major league ballpark\(^1\) and increases with energy, making IACTs an excellent match for extending the energy coverage of satellite-based detectors (area close to the cross-sectional area of a baseball player), especially when considering rapidly dropping fluxes with increasing energy. The sensitivity ($S$) of IACTs can be substantially improved by increasing the collection area from 0.1 km\(^2\) to $\geq$ 1 km\(^2\). While this benefits all science topics, it particularly improves sensitivity in a regime where the current instruments are photon limited, e.g. short AGN flares, GRBs and the measurement of energy spectra at multi-TeV energies and beyond.

- Another strength of the IACT technique is its good angular resolution. An additional factor of a few improvement would go a long way towards mapping the morphology of extended sources in our galaxy. Better angular resolution also helps to substantially reduce the isotropic background from cosmic rays. This increases the point source sensitivity linearly

\(^1\) Typically $\sim$ 100 000 m\(^2\).
in an energy regime where current IACTs are limited by cosmic-ray background, namely between 100 GeV and a few TeVs.

- A lower energy threshold is important to expand the horizon of the observable universe for IACTs. This requires a decrease of the energy threshold of existing instruments from 100 to 10 GeV, where the universe becomes transparent to $\gamma$ rays.
- A wider field of view is important for extended emission regions in our galaxy, to allow limited surveys of the extragalactic sky and to improve the prospects for the detection of GRBs. Furthermore, the sensitivity to galaxy clusters and pair-halos [66] around blazars could be substantially improved.

3. The large array concept

Current IACT arrays built for TeV $\gamma$-ray astronomy are the HESS and VERITAS observatories, and most recently the MAGIC-II stereo system [67]. HESS and VERITAS each consist of four telescopes with a spacing of $\sim$100 m. The key instrument design goals are: a factor of ten better sensitivity and collection area, a better angular resolution, and a lower energy threshold compared with current instruments. A natural progression of the IACT technique is to consider large arrays of imaging telescopes. Simplistic scaling of the number of telescopes suggests that sensitivity improves with $\sqrt{N}$ ($N$ = number of telescopes). This would require approximately 400 telescopes to reach an order of magnitude better sensitivity. In the following, we discuss the principal design considerations that show that large arrays provide significantly better performance improvements than expected from $\sqrt{N}$ scaling. This is largely due to the better reconstruction capabilities of air showers whose shower cores fall within the array boundaries, thereby providing ‘contained’ events. As a consequence, much fewer telescopes ($\sim$100) are required to reach the stated design goals, opening the path for a cost effective construction of IACT arrays that meet the design goals stated in the previous section.

To identify the most effective means of improving upon sensitivity, it is instructive to consider the limitations of existing IACT arrays. Figure 1 shows the differential flux sensitivity\(^2\) of current generation IACTs (HESS and VERITAS), the Fermi Gamma-Ray Space Telescope and an approximate estimate of future IACTs such as AGIS/Cherenkov telescope array (CTA) [68, 69]. The physical limitation for flux sensitivity essentially occurs for three distinct reasons corresponding to different energy regimes:

- The sensitivity above $\sim$5 TeV is photon-count limited (blue line in figure 1) and can only be improved by increasing the collection area. A ten times larger area would increase the sensitivity by an order of magnitude, since background contamination becomes negligible due to a falling cosmic-ray spectrum and reconstruction improves for bright—thereby well defined—Cherenkov light images.

- The medium energy regime between 100 GeV and 5 TeV (green line in figure 1) is generally dominated by background that arises from cosmic-ray showers. A better discrimination between the characteristics of hadronic cosmic-ray showers and $\gamma$-ray

\(^2\) Note that the differential flux sensitivity $S$ versus energy is different than the often quoted integral flux sensitivity above a given energy. The differential flux sensitivity for a point source shown here requires a 5$\sigma$ detection per quarter decade in energy. Exposure times of 50 h for IACTs are assumed while a 1 year exposure is used for Fermi (background for extragalactic observations assumed).
The differential flux sensitivity $S$ (5σ point source detection per quarter decade in energy is required) is shown in units of erg cm$^{-2}$ s$^{-1}$ (power) for various existing/future γ-ray telescopes: Fermi (1 year), the HESS or VERITAS (50 h) observatory and a future large array of IACTs (AGIS/CTA). Note that improved sensitivity means a lower flux can be detected. The flux sensitivity for a future IACT is only an idealized approximation [70] in the mid-(green) and high-(blue) energy regimes and does not take into account additional background from NSB at low (red) energies. More accurate sensitivity estimates are currently under study based on extensive Monte Carlo simulations and specific cases can be found in Bernlöhr [71], which are close to the curve presented here at mid and high energies.

- The energy regime below 100 GeV (red line in figure 1) is limited by an additional background component. While cosmic rays are still a significant contributor, the most severe background arises from Poisson fluctuations of the night sky background (NSB) light. For a given telescope mirror area, the latter poses a ‘wall’ of accidental triggers and sets a limit for triggering a Cherenkov telescope and its ability to detect low-energy γ-ray showers characterized by low-light levels. While the night sky becomes a dominant limitation at 100 GeV for a 12 m telescope, the energy threshold $E_{\text{thres.}}$ can be lowered. $E_{\text{thres.}}$ can be reduced by increasing the amount of Cherenkov light collected either by using a larger light collector, higher quantum efficiency (QE) photodetectors and all measures that minimize light losses in the instrument. The energy threshold of IACTs scales approximately with $A_{\text{mirror}}^{-1/2}$ and $QE^{-1/2}$, the mirror area and the QE, respectively.
However, when approaching energies as low as 30 GeV, intrinsic shower fluctuations (a few secondary particles) in the Cherenkov light signal from a γ-ray leads to poor hadron rejection. Furthermore, the Cherenkov light images contain significant contamination from accidental NSB photoelectrons compromising the image analysis.

Design considerations for a large array require first and foremost a good understanding of the lateral distribution of Cherenkov light produced by the electromagnetic cascade from a γ-ray shower. In figure 2(a), we show the simulated lateral distribution of Cherenkov light for γ-ray events of various energies. The density of photoelectrons versus core distance remains relatively flat for γ-ray primaries below 1 TeV and exhibits a characteristic ‘rim’ [73] at approximately 120 m for an observing altitude of 2400 m above sea level. The rim arises from an increasing Cherenkov angle with air density, as particles penetrate deeper into the atmosphere. For example, the Cherenkov angle increases from 0.3° at 15 km atmospheric height to 0.8° at 7 km, while the distance between the emission height and detector elevation decreases. Therefore, Cherenkov light from particle tracks close to the shower axis is accumulated at a characteristic core distance, namely the ‘rim’. The region within the rim is often referred to as the ‘Cherenkov light pool’ and covers an area of ~50 000 m².

Cherenkov light detected at core distances beyond the ‘rim’ originates from lower energy particles prone to substantial multiple scattering, causing light to be directed several degrees...
from the $\gamma$-ray primary’s arrival direction. This allows the detection of showers at core distances much beyond 120 m; even detection at 1 km is possible, but depends on the primary energy. Generally, the detection of a $\gamma$-ray shower is limited by the density of Cherenkov photons, because close to $E_{\text{thres}}$, Cherenkov light images become contaminated with photons from the NSB. For example, a light collector with a given mirror area of 100 m$^2$ and set threshold for accepting images that corresponds to 3 pe m$^{-2}$ (figure 2(a)), is sensitive to the detection of 200 GeV $\gamma$ rays with a collection area of 50 000 m$^2$. At the same time, this instrument is also sensitive to the detection of 1 TeV (10 TeV) $\gamma$-ray showers at a core distance up to 300 m (1000 m) with corresponding collection areas of 280 000 m$^2$ (3 km$^2$)$^3$.

Larger core distances also imply a larger angular displacement of the Cherenkov light image centroid from the arrival direction of the $\gamma$-ray primary. This is shown in figure 2(b) showing the ‘Size’ parameter in photoelectrons versus angular displacement from the $\gamma$-ray source. ‘Size’ is a measure of the Cherenkov light image brightness and to first-order scales with the Cherenkov light density and primary energy for a given core distance. A characteristic ‘rim’ feature also appears in figure 2(b) at 1.2$^\circ$ (120 m) for energies up to $\sim$2 TeV. Furthermore, an important requirement for the detection of multi-TeV $\gamma$ rays with large core distances, necessary for large collection areas of individual telescopes, follows from figure 2(b): a field of view sufficiently large to accept off-axis photons up to $\sim$4$^\circ$ is required. The relation between core distance and angular displacement of Cherenkov light images from the primary arrival direction was studied in detail [72] and has become a key technical consideration for large arrays.

In summary, results from studies of the lateral and angular Cherenkov light distribution show that wide field of view instruments are required [72, 74] for detecting showers with large core distances, which translates into a bigger collection area. For large arrays of IACTs, this is very relevant, since detecting showers at large core distances is a prerequisite for increasing the number of telescopes participating in the reconstruction of individual showers. The number of telescopes viewing the air shower has important consequences on angular resolution and will be discussed in the following section.

3.1. Angular resolution

The IACT technique already provides the best angular resolution of any astronomical technique above 0.1 MeV; the typical angular resolution achieved by HESS and VERITAS is 0.1$^\circ$ for individual events. It is again instructive to consider the principal limitation to the angular resolution for IACTs. A limit to the angular resolution arises predominantly from the air shower physics and the limited collection efficiency of Cherenkov photons; studies by Hofmann [75] indicate that an order of magnitude better angular resolution may be possible at multi-TeV energies. This estimate requires $\sim$10% coverage of the light pool that is impractical while simultaneously trying to achieve a large array size. While the full improvement may not be attainable with a real-world instrument (typically only few $\times 10^{-3}$ of all Cherenkov photons detected), it may be possible to get close to that at multi-TeV energies and at lower energies with an array with variable telescope spacing, a ‘graded array’.

One might expect that the angular resolution of an IACT array depends on the telescope multiplicity, the resolution of the imaging camera (assuming perfect telescope optics) and light

$^3$ A core distance of 1 000 m translates into an image that is $\sim$10$^\circ$ offset from the arrival direction of the $\gamma$ ray suggesting a field of view of 20$^\circ$, which is substantially larger than what is currently considered even for future IACTs.
Figure 3. The image of a 460 GeV $\gamma$ ray at a core distance of 190 m is shown for three different pixelations: 0.28°, 0.14° and 0.07° (Courtesy: Konrad Bernlöhr). The yellow ellipses indicate the image shape based on a second moment analysis. The yellow line is derived from the major image axis and the red cross and circle indicate the actual and the reconstructed shower direction using multiple telescopes, respectively.

Figure 4. Left: the reconstruction of the arrival direction based on the simulation of multiple Cherenkov light images is shown [76]. Right: the angular resolution is shown versus the number of telescopes participating in the reconstruction.

collection (includes mirror size and QE of photodetectors). It turns out, that the most dominant factors rank ordered are telescope multiplicity and to some extent camera pixelation (see figure 3), while telescope mirror size is mostly relevant for the energy threshold. Simulations of a 50-telescope array with 50 m spacing [76] highlight the dependence of angular resolution on the number of telescopes participating in the angular reconstruction. Figure 4 (left) shows Cherenkov light images of eight telescopes superimposed on the sky: the intersection of the lines shows the point of origin for the $\gamma$-ray primary. Figure 4 (right) shows the dependency of angular resolution as a function of the number of telescopes participating in the reconstruction—the most dramatic improvement for 1 TeV showers occurs between 2 and $\sim$10 telescopes. For a telescope multiplicity above 10, the reconstruction becomes over constrained and improves further, but with diminishing returns.
Intuitively one would also expect that pixel size influences the reconstruction of the arrival direction of γ-ray showers. While this is generally the case for a pixelation $\geq 0.2^\circ$, the key question is to determine the optimum pixelation and the regime of diminishing return for resolving shower images, with the aim of improving angular resolution and rejecting background. A study of pixel sizes ranging from 0.07° to 0.28° by Bernlöhr [71] suggests that pixels smaller than $\sim 0.20^\circ$ do not improve flux sensitivity for energies above 1 TeV. Pixel sizes of $\sim 0.10^\circ$ provide somewhat better performance at lower energies especially below 100 GeV. Similar studies by Funk and Hinton [76] also find only marginal improvements in angular resolution with a finer pixelation. While a pixelation of $\sim 0.05^\circ$ performs somewhat better at energies of 0.1, 0.3 and 1 TeV, the improvements over a $\sim 0.10^\circ$ pixel size are nevertheless found to be marginal [76]. This analysis is based on standard Hillas parameters [77] and does not preclude substantial improvements with more advanced analysis methods. Somewhat different conclusions about the importance of pixelation were reached by Fegan and Vassiliev [78], suggesting that going from 0.13° to 0.016° pixelation provides at least a 25% improvement in angular resolution and a 40% overall improvement in sensitivity below 100 GeV. The improvement of sensitivity with a finer pixelation motivates the design of telescopes with high-resolution cameras [79].

While these improvements are not in conflict with other results, as they use different analysis methods, further studies are required. A major factor that will determine the ultimate choice of pixel size is cost optimization and is strongly coupled to technical developments of future instrumentation.

In summary, angular resolution is expected to increase substantially (at least a factor of 2–3) for a large array of IACTs. Further improvements are likely especially when using image analysis algorithms that are optimized for large arrays. The most critical design parameters that determine the number of telescopes in the reconstruction for a given γ-ray energy are field of view, mirror size and telescope spacing.

3.2. Background rejection

The numerous background from cosmic-ray showers was the main challenge for ground-based γ-ray astronomy till the late 1980s, when, for the first time, the effective rejection power of the imaging technique [77] was demonstrated with a single IACT [1]. Further, substantial improvements were made when stereoscopic IACT systems were put into service [3, 4, 80]. Nevertheless, background from cosmic-ray showers is still a limiting factor in the low- and mid-energy regimes. The next major step could come with the introduction of large arrays of wide field of view IACTs, that allow the detection of ‘contained events’ that should also yield additional hadron rejection through multiple views of air showers.

There are two distinct methods to reject background from hadrons. The first line of defense against these unwelcome events is given by angular resolution when searching for γ-ray point sources. The much improved angular resolution (factor of a few) of a large array will increase the sensitivity for point sources by the same amount. This is because the signal remains unaffected and the background is reduced by a factor of $\sim 10$, assuming a reconstruction accuracy of 0.03° compared with 0.1°. This yields a factor of $\sim 3$ better sensitivity. Secondly, the morphology of hadronic showers and their Cherenkov light images also provides a high level of

Note that angular resolution also helps to reduce background from cosmic-ray electrons, which become the prevailing background, once cosmic-ray hadrons are mostly rejected.

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background rejection (referred to as $\gamma$/hadron separation) capabilities, the only effective means of improving sensitivity for extended emission regions.

Current IACT arrays record a typical event rate of 300 Hz of predominantly cosmic-ray showers. This already includes substantial suppression of hadronic showers at the trigger level. The offline point-source analysis reduces this event rate to typically $\sim 0.01$ Hz, depending on the specific analysis applied. However, a large fraction of the background reduction is due to angular resolution (factor $\sim 100$), whereas another factor of $\sim 300$ arises from the $\gamma$/hadron separation. Further improvements in the hadron rejection are possible, but it is also important to consider the limitations. A hard physics limit for distinguishing hadronic primaries from $\gamma$-ray-induced showers may arise from interactions in which a large fraction of the cosmic hadron’s energy is converted into electromagnetic particles in the initial interaction [81]. Theoretical predictions [82] suggest that for 17 TeV protons in collisions with nitrogen, more than 3/4 of the primary energy is converted into electromagnetic particles for 1/1000 of all events. While this might indicate that an irreducible hadronic background may be persistent at the 0.1% level, to the author’s knowledge, there are no accelerator measurements available at this time to unequivocally confirm these estimates. Furthermore, for a given energy, the first interaction for a proton in the atmosphere would on average occur at a lower atmospheric height, providing some distinguishing power when compared with $\gamma$-ray showers.

Assuming these theoretical limitations are valid, current instruments may already approach a physics limit and a large factor of additional discrimination power may be difficult. On the other hand, existing instruments are far from resolving the shower images (see figure 3) and higher resolution images may help to better recognize hadronic cascades that are $\gamma$-ray like. An array of wide field of view instruments may also be capable of picking up subshowers from early hadronic interactions and help the $\gamma$/hadron rejection capabilities of a future large array. Typical cosmic-ray shower Cherenkov images are often spread out and are much broader and longer in angular extent. Indications from Monte Carlo simulations are that a large array viewing a shower from multiple view points is bound to provide improved $\gamma$/hadron separation capabilities, particularly when wide field of view cameras are employed. Extensive simulations are required to quantify sensitivity improvements, which are likely specific to the design of a telescope array. A hadron suppression of a few $10^{-4}$ was suggested by Hofmann [75] indicating substantial improvement over current instruments. It is beyond the scope of this paper to give more details of the $\gamma$/hadron rejection capabilities of a future large array.

In summary, while background rejection with current IACTs is already impressive, further improvements are definitely possible for point-source observations and would help to improve the sensitivity at medium energies, i.e. 100 GeV–5 TeV and at energies below 100 GeV. Further improvements are subject to extensive Monte Carlo simulations and involve the production of at least $\sim 10^9$ events since hadron rejection with IACTs is already very impressive.

3.3. Energy resolution

The primary $\gamma$-ray energy can be estimated by the amount of Cherenkov light emitted by an electromagnetic cascade (see figure 2). Ideally one would like to measure the shower geometry including core distance, height of shower maximum and also sample the light density in the light pool with a large number of telescopes. The step from a single telescope [83] to current arrays of telescopes [84] has improved the energy resolution of the IACT technique from typically 30–40% to 10–20% since arrays allow the measurement of the shower impact parameter and
the height of shower maximum. An energy resolution of 9–12% was reported by [85] for the 1–100 TeV energy regime.

One of the advantages that large arrays will bring is the measurement of the energy resolution using subarrays and provide an experimental verification of the resolution predicted from simulations. Furthermore, a better sampling of the light pool, higher resolution images, a wider field of view to avoid image truncation, a better shower core and shower maximum height measurement are expected to improve the energy resolution.

4. Technology for future IACTs

Implications from the previous section suggest that a large array (~100 telescopes) with a factor of 10 larger collection area could yield a factor of 3 better angular resolution, improved background rejection and order of magnitude better sensitivity. While there is essentially unanimous agreement among the different air Cherenkov groups on the large array concept, there are different approaches regarding the implementation and technical concepts proposed by the AGIS [68] and CTA [69] collaborations.

The technology required for implementation of the large array concept depends on the energy range to be covered and can be divided into three principal regimes:

1. Low-energy regime (20–100 GeV): the reconstruction of electromagnetic showers with these primary energies is limited by the number of secondary particles and subsequently increased fluctuations and low Cherenkov light density. Large mirror sizes (17–28 m) and (possibly) in combination with high QE photodetectors are necessary to explore this energy regime. Although the detection of sub-100 GeV $\gamma$ rays was explored and successfully demonstrated with the single MAGIC telescope [26], current efforts are underway to apply the stereoscopic technique with MAGIC-II [86] and HESS-II [87]. Results are expected in the next few years and will help to evaluate further improvements of the IACT technique at the lowest energies. Given the high cost associated with large telescopes, only a small number of sub-100 GeV telescopes are foreseen to complement the sensitivity of a future large array at the lowest energies.

2. Medium-energy regime (0.1–5 TeV): the IACT technique has proven to be very effective at these energies and offers excellent sensitivity; typically, 1% of the Crab Nebula flux at 200 GeV can be detected within less than 50 h with a significance of 5$\sigma$. The further development of the medium-energy regime is given particular emphasis, since it is the domain of the IACT technique and already provides the best flux sensitivity of any ground-based $\gamma$-ray telescope. Here, the large array concept, which provides contained events and multiple-view points, is the most promising approach for giving 0.1% Crab sensitivity. An expansion to the large array concept requires relatively wide field of view instruments, ideally of the order $\sim$10°. New technologies, namely optical telescope designs with minimized off-axis aberrations and high-resolution wide field of view modular camera designs are being explored. The large number of telescopes will also require a cost effective approach and performance optimization.

3. High-energy regime (5–100 TeV): IACTs operating in this regime are photon count limited and a large effective area (10 km$^2$) is the key to an improved sensitivity over existing instruments. Since air showers at these energies provide plenty of Cherenkov photons, this regime could be covered with relatively small telescopes (~10 m$^2$ mirror area)
and wide field of view and compact cameras. While the cost of small telescopes is relatively low, the camera cost becomes dominant and the development of low-cost cameras becomes important for achieving a large area coverage with telescopes for the high-energy regime.

In the following subsections, the key technologies relevant for the design considerations of a large array are discussed.

4.1. How to build a telescope?

Current generation IACTs are typically based on a tessellated mirror structure (figure 5 left) that either forms a parabola [5] or a spherical reflector shape, the latter is also known as the Davies–Cotton design [88]. Both optical designs deliver an adequate point spread function (PSF) for current generation, moderate field of view IACTs (3.5°–5° across) and pixel sizes of ~0.1°. A parabolic reflector is isochronous as it does not introduce any spread in the arrival time of a plane wavefront of photons received in the focal plane. The short Cherenkov flashes (~5 ns) are preserved in isochronous designs, which is important in the low-energy regime, where Cherenkov light images get contaminated with noise from NSB fluctuations of similar magnitude. A disadvantage of the parabolic design is the presence of significant off-axis aberrations (coma) that are pronounced for Cherenkov light images offset from the optical axis. The Davies–Cotton structure, originally designed as a solar light concentrator, provides compensation against spherical aberrations and coma. Nevertheless, global coma is still dominant for off-axis images and has significant consequences for the design of a wide field of view telescope.
Generally, off-axis distortions can be reduced by increasing the $f$-number ($f/D$, with $f =$ focal length and $D =$ diameter of reflector), since coma scales with $1/f^2$ [89]. Existing IACTs have $f/D$ ratios between 1.0–1.2 (VERITAS, HESS and MAGIC), which is sufficient for a field of view of $5^\circ$. A larger field of view can be accommodated by increasing the $f/D$ ratio; however, the plate scale (conversion of angular size to physical size in the focal plane) becomes unwieldy: the typical camera size of current IACTs is already $\sim 2\text{ m}$ in diameter. An even larger plate scale also requires a large physical size of the photodetectors in the focal plane and consequently a large area to be covered with costly photosensitive material. This is the major tradeoff when considering relatively inexpensive prime focus telescopes. Prime focus optical designs, including the Davies–Cotton and the parabolic design can in principal provide a PSF of $0.05^\circ$ (rms) over a $10^\circ$ field of view but require $f/D = 2.5$ and 2.7, respectively. Unless one relaxes the requirements for pixelation and optical PSF and consequently the $f/D$ ratio, wide field of view prime focus instruments require substantially more complex mechanical support structures, large camera sizes and incur significant obscuration at the 25% level [90]. Lower resolution ($\geq 0.15^\circ$) wide field of view telescopes can be achieved with prime focus instruments using an $f/D = 1.5$.

High resolution, wide field of view imaging of Cherenkov light images may require other solutions for the optical design. Wider field of view telescopes are possible through the use of a second optical element for reducing off-axis aberrations. Two such optical systems have been proposed to be used for IACTs. A wide field of view can be achieved with a Schmidt telescope in which a corrector plate deforms the wavefront so that it is mostly free of spherical aberration when arriving at the spherical mirror. The Schmidt corrector is a weak aspheric transparent optical element of a thickness of less than 20 mm. A design with an $f/D = 0.8$ provides a polychromatic resolution of better than $0.02^\circ$ across a $15^\circ$ field of view [91]. A moderate size telescope with 7 m primary diameter would have a focal length of 5.6 m, whereas the corrector plate is positioned at a distance twice the focal length from the primary. Requirements for the positioning accuracy of the Schmidt corrector are relatively relaxed (1 cm decentering and 10 cm along the optical axis). A segmented corrector plate made from acrylic has yet to be built and demonstrated but could be cost effective. The transmission of dominantly blue Cherenkov light (follows $1/\lambda^2$ spectrum, with wavelength $\lambda$) is an important consideration; however, when folding in atmospheric absorption, a cutoff below 300 nm, as is typical for acrylic, is not necessarily prohibitive.

A different approach to a wide field of view instrument is given by the use of a secondary mirror and has been extensively discussed by [92]. Aplanatic two-mirror telescopes by definition have excellent compensation against spherical aberrations and coma and are in theory the solution to wide field of view instruments. A specific type of aplanat has been suggested by Vassiliev et al [92] for use in IACTs, the Schwarzschild–Couder telescope (see figure 5 right). It consists of an 11.5 m diameter primary and a 6.6 m secondary mirror assembly, with the focal plane situated about 1.7 m from the secondary. The correction of spherical aberrations and coma is achieved through the concave aplanic mirrors, which are configured so that they demagnify the image in the slightly curved focal plane. One of the key advantages compared with the Davies–Cotton reflector is its relatively compact design with a short focal length and consequently a small plate scale. This allows the use of compact photodetector assemblies such as multianode-photomultiplier-tubes (MAPMTs) and potentially silicon photomultipliers (SiPMs). Technological challenges are the cost effective mass production of the aspherical mirrors. Replication techniques such as electroforming [93] and cold glass slumping are now
4.2. How to build a camera?

A wide field of view is motivated by astrophysical considerations and also the large array concept. At least for the medium- and high-energy regimes, the field of view is likely to increase compared with current instruments. In addition, the exploration of high-resolution imaging for the IACT technique with finer pixelation (∼0.05° or less) will require a very different camera design for future instruments; a highly modular approach combined with cost effective, low-power readout electronics, high voltage supply and slow control are required. Current IACT cameras with field of views of 3.5°–5° are made from individual ∼1 inch photomultiplier tubes and have pixel numbers between 500 and 1000. A 10° field of view with, e.g. 0.05° pixelation involves ∼4 × 10^4 pixels. Although pixel size and the exact field of view will be a matter of optimization and is beyond the scope of this paper, the order of a few times ∼10^4 pixels are likely to populate future high-resolution—wide field of view cameras. This, however, is only possible if the cost per pixel can be substantially reduced from existing instruments. A promising approach is the use of a demagnifying optical system as discussed in the previous section.

Figure 6 shows a modular camera design as could be used in combination with an aplanatic telescope and a demagnified plate scale. The integration of MAPMTs has two distinct advantages: substantially lower cost and very effective coverage of the focal plane with

![Figure 6](http://www.njp.org/)

**Figure 6.** Left: a modular camera design, in this case, a design drawing for an AGIS camera is shown (Credit: Jim Buckley). Right: a camera module consisting of a 64-pixel MAPMT is shown.

available [94, 95]. Complications of the Schwarzschild–Couder telescope arise from the high positioning accuracy (∼1 mm) required for the secondary mirror and therefore requires a high-precision active mirror control system.

While the technologies to solve the challenges of some of these complications arising from two element telescopes are available, cost and overall performance of an array made from conventional and from lower resolution telescopes versus high-resolution instruments will decide which types of telescope will be used for the different energy regimes. While small field of view—large telescopes—for the low-energy regime, will likely consist of prime focus instruments, the medium-energy regime could gain substantially (performance and cost) from high-resolution wide field of view telescopes using a second optical element. In the following, we discuss the focal plane instrumentation and its connection to the telescope design.
photosensitive material. A camera that comprises of Hamamatsu H8500 MAPMTs [96] with 64 channels has a total dead space of just 11%, which is excellent compared with existing IACTs that require the use of light concentrators. A slightly curved focal plane as is the case in the Schwartzschild–Couder design could be accommodated in the mechanical design. IACTs for the low-energy regime with a smaller field of view could be based on the Davies–Cotton design and the substantially smaller number of pixels would make the use of individual PMTs in the focal plane efficient.

The development of more efficient photodetectors is an active branch of experimental research. Photomultipliers with higher QE such as the Hamamatsu Super-Bialkali and Ultra-Bialkali photocathodes [97] with QE values of 35% and in excess of 43% (at 350 nm) are promising for application in IACTs especially for exploring the low-energy regime with faint Cherenkov light images. Other approaches involve Silicon photomultipliers, in which an array of avalanche photodiodes operates in Geiger mode. A common readout of the array provides excellent single photoelectron resolution as discussed in [98] and is still in the development phase.

Readout electronics of the analog signals from the photodetectors of IACTs are based on either flash-analog-to-digital converters or analog sample and hold memories, and 5 Gsamples s$^{-1}$ are now possible. While both devices are used in current generation IACTs, the latter hold promise for a cost effective solution to high-pixelation/low-power cameras and can be integrated in an application-specific-integrated circuit (ASIC) [99, 100].

Triggering an IACT occurs at the camera level by setting a threshold to the analog pulse from the photodetectors at (typically) a few photoelectrons. The trigger system then proceeds to perform a comparison between neighbor pixels on timescales of $\sim$5 ns to identify triggers from fast Cherenkov light images that should have a continuous structure across several pixels in the camera. In addition, an array trigger can be used to search for coincidences between telescopes that are struck by the Cherenkov light wavefront. Trigger systems of this type have been implemented in HESS and VERITAS and operate successfully in reducing the accidental rate from NSB and also provide moderate cosmic-ray rejection at the array trigger level.

Advanced trigger systems are under development, since modern high-speed field-programmable-gate-arrays with $\sim$2 ns sampling rates are now available. They allow the real-time calculation of image parameters that can be used in the stereoscopic analysis and array level processor (topological array trigger) to determine the likelihood that an event is a $\gamma$ ray, a cosmic-ray shower or accidental NSB fluctuation [99, 101]. This scheme is applicable to systems where high camera trigger rates (few MHz) and deadtime limitations of the data acquisition system are prevalent.

A different approach has been proposed and is applicable to data acquisition systems that are essentially deadtime free and/or where camera rates (10 kHz) do not pose a limiting factor [102]. In this scheme, the data are first sent into a large buffer memory inside the camera and then the stereoscopic analysis is performed via a fast ethernet link.

In summary, many technological advances are being made in camera development including photodetectors, readout and triggering. While there are competing approaches, some of these will find applications in the construction of IACTs for the low-energy, medium-energy and high-energy regimes. Most importantly, all the critical technologies required to build a large IACT array are available.
5. Summary

Large arrays of IACTs would offer a unique opportunity to explore the high-energy universe and deliver important astrophysical information about relativistic particles permeating galactic and extragalactic space. A factor of 3 improved angular resolution, a ten times larger collection area and a better cosmic-ray rejection are key ingredients to deliver an order of magnitude better sensitivity over existing ground-based $\gamma$-ray telescopes. Large arrays of IACTs are the logical follow-up to the Fermi $\gamma$-ray space telescope and the current generation of IACTs.

While there are different ideas of how to build telescopes for different energy regimes, a common general view seems to emerge: a graded large array with different size telescopes, including large reflectors for the low-energy regime, a core array of mid-size telescopes for the primary energy regime of 100 GeV–10 TeV and a system of smaller instruments for the 10–100 TeV. Two major collaborations are currently pursuing the concept of a large array, the advanced gamma-ray imaging system (AGIS) collaboration (see www.agis-observatory.org) in the western hemisphere (US and the Americas) and the CTA collaboration (see www.cta-observatory.org) involving many countries from the European Union.

Acknowledgments

This research was supported by grants from the US Department of Energy. FK thanks many colleagues from the MAGIC, Milagro, HESS, VERITAS, AGIS and CTA collaborations for many useful discussions about future ground-based telescopes.

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