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# Cherenkov Telescope Array – The Future of Ground-Based Gamma-Ray Astronomy

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**Abstract.** Very-high energy (VHE; $E \gtrapprox 100$ GeV) $\gamma$-rays provide a unique probe for non non-thermal processes in the universe. The ground-based Imaging Air Cherenkov Technique for detecting VHE $\gamma$-rays has matured, and a fast assembly of inexpensive and robust telescopes is possible. The goal for the next generation of instruments is to increase their sensitivity by a factor $\gtrsim 10$ compared to current facilities, to extend the accessible $\gamma$-ray energies from a few tens of GeV to a hundred TeV, and to improve on other parameters like angular and energy resolution. I discuss the key physics goals and resulting design considerations for the Cherenkov Telescope Array (CTA), a project for a new generation of highly automated telescopes for $\gamma$-ray astronomy. The technical solutions chosen for CTA and the status of the project are discussed.

## 1. Introduction

Very-high energy (VHE) $\gamma$-rays are produced in nonthermal processes in the universe, namely in galactic objects like pulsars, pulsar-wind nebulae, supernova remnants (SNR), binary systems containing compact objects, or OB associations. Among the extragalactic VHE $\gamma$-ray sources are active galactic nuclei (AGN), particularly blazars and radio-galaxies, and starburst galaxies. Galaxy clusters and gamma-ray bursts are also potential, although not yet discovered, sources of VHE $\gamma$ rays. Apart from the astrophysics of specific astronomical objects, $\gamma$-ray astronomy can be used to search for the annihilation of dark matter particles, and for studying the transparency and history of the universe. Further fundamental physics searches, like for the violation of Lorentz invariance, can be performed. For recent reviews, see, e.g., [1, 2].

Upon reaching the Earth's atmosphere, VHE $\gamma$-rays interact with atmospheric nuclei and generate electromagnetic showers. The showers extend over several kilometers in length and few tens to hundreds of meters in width. At VHE, the shower particles are stopped high up in the atmosphere. A sizeable fraction of the charged secondary shower particles, mostly electrons and positrons in the shower core, move with ultra-relativistic speed and emit Cherenkov light. Imaging atmospheric Cherenkov telescopes reflect the Cherenkov light onto multi-pixel cameras that record the shower images.

## 2. Towards a precision gamma-ray astronomy

Despite the promising achievements of current-generation Cherenkov telescopes [1], there are limitations that future instruments will need to overcome: current instruments are sensitive in an energy range of $\gtrsim 80$ GeV$-$50 TeV. At the low energy end, limitations come from the background from atmospheric hadronic (and electronic) showers. At the high end, the limit is statistics; due to the lack of a calibrated cosmic $\gamma$-ray source, spectral reconstruction is limited by systematic bias and statistical uncertainties; the aperture of Cherenkov telescopes is limited to a typical field of view (FOV) of $3-5°$ diameter, as is the angular resolution, currently around a few arcmin. Also, current facilities are rather poorly automatized. From a physics point of view, there are strong arguments to improve in the following aspects: decrease the energy threshold to few tens of GeV; acquire sensitivity beyond 50 TeV; increase sensitivity in the core range (100 GeV$-$50 TeV); improve energy and angular resolution. Cherenkov Telescope Array (CTA) is a next-generation ground-based project which aims at implementing all these improvements.

### *2.1. Low-energy physics (sub-50 GeV)*

MAGIC has opened the field of sub-100 GeV $\gamma$-ray astronomy [3]. Observations with higher sensitivity in this region will have important consequences for galactic and extragalactic physics. By studying the sub-50 GeV energy band, CTA could provide the final answer to the acceleration mechanism in pulsars. A high sensitivity in the low energy regime is also vital for studying AGNs, which typically exhibit rather steep power-law spectra (due to the increasing suppression of $\gamma$-ray flux with energy by the extragalactic background light). Further, low-energy sensitivity is vital to complement the catalog of *Fermi*-LAT detected $\gamma$-ray emitters with a possibly larger significance than obtainable by LAT at its high-energy end. This will provide a unique way to understand the nature of the tens of yet unidentified *Fermi*-LAT detected sources [5].

### *2.2. High-energy physics (above 50 TeV)*

Typical astrophysical $\gamma$-ray spectra have bimodal distributions with one peak at lower energies due to synchrotron emission, and a second peak at higher energies due to inverse Compton scattering of VHE electrons on seed infrared/optical photons. For galactic objects, one may expect to observe VHE power-law $\gamma$-ray spectra with cutoffs due to intrinsic mechanisms. $\gamma$-rays from distant blazars suffer a severe attenuation after pair production with local IR-UV photons of the extragalactic background light (EBL). In all current IACT data, the evidences for spectral cutoffs and steepening are rather poor. There is no simple justification for this. CTA will explore this region with unprecedented sensitivity. This will allow to understand the acceleration mechanism in galactic objects like SNRs, and discriminating hadronic/leptonic models. The high energy region is also important for identifying PeVatrons, i.e. cosmic-ray accelerators to TeV/PeV energies. Detecting outbursts ("flares") from distant AGNs at super-TeV energies would allow to increase the prospects for firm limits on Lorentz invariance violation.

### *2.3. Core energy region (0.1$-$50 TeV)*

CTA will provide an increase of the sensitivity in this core energy region by at least a factor 10 as compared to the current IACTs, reaching a level of $10^{-3}$ C.U.[1] sensitivity in this range. This will promote $\gamma$-ray astrophysics to a *$\gamma$-ray astronomy*. In fact, for the first time, CTA will allow for a full VHE sky survey, with approx. a thousand new VHE $\gamma$-ray sources expected to be detected.

An increase in sensitivity will, by reducing the required observation times, allow more follow-up observations and higher time resolution of variable sources. The current telescopes are sensitive enough to detect variations on timescalew of minutes. CTA will allow a sub-minute resolution, and thus to understand the complex phenomena of $\gamma$-ray flares, directly connected to the acceleration mechanisms and the local environment. Morphological studies will profit from reduced required observation times. These are of importance to study spatially extended $\gamma$-ray emitters, like SNRs. An increase of the angular resolution by a factor $4-5$, down to

[1] The differential photon flux of the Crab nebula between 60 GeV and 9 TeV is [4] $\mathrm{d}F/\mathrm{d}E = (6.0 \pm 0.2)10^{-10}(E/300\,\mathrm{GeV})^{a+b\log_{10}(E/300\,\mathrm{GeV})}\ \mathrm{TeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ with $a = -2.31 \pm 0.06$, $b = -0.26 \pm 0.07$.

0.02 arcmins (current theoretical limits are discussed in [6]), will reduce source confusion and improve collaboration with instruments observing at other wavelengths.

## 3. General design ideas

To meet the physical requirements specified in the previous section and to maintain an overall high technical performance, the CTA concept is based on few general ideas: Increase the array from currently 4 (H.E.S.S., VERITAS) to $\approx 100$ telescopes; distribute them over a large area ($1 - 10$ km$^2$); make use of telescopes of $2 - 3$ different sizes; take advantage of well-proven technology of current IACTs; high automatization and remote operation; run array as observatory and open the facility to the astronomy and astrophysics community.

An increase in sensitivity over the full energy range can only be achieved by combining many telescopes distributed over a large area of at least 1 km$^2$ and using telescopes of $2 - 3$ different sizes: several medium size telescopes (MST) of 12 m, few large size telescopes (LST) of 24 m diameter, and probably several small size telescopes (SST) of 7 m diameter. The number of the telescopes, their size, configuration and the overall performance are under investigation.

The LSTs detect sub-100 GeV photons thanks to their large reflective area. Technologically, they are the most challenging telescope type. A design is currently under development. Several tens of MSTs will perform the $\gamma$-ray detection in the core energy region. Those telescopes will be based on the experience gained with the H.E.S.S. and MAGIC telescopes. The main goal is to reduce cost and maintenance efforts. The MSTs constitute the core of the array, and will also perform the fundamental task of vetoing the LST triggers to reduce hadronic background. The MST design is currently studied and the construction of a prototype is expected in few years from now. In case 3 different telescope sizes are required, several tens of SSTs will complete the array to perform the super-TeV search, increasing the effective collection area of the array. Very simple in construction, contributing only a small percentage to the cost of the full array.

The trigger systems will support different operation modes. In the “deep field” mode, all telescopes will be pointed to the same sky position to maximize the sensitivity. In a more flexible mode, parts of the telescopes could point to different positions, with few telescopes making follow-up observation of single sources as, e.g., to monitor blazar activity. Finally, the array can be operated in a “wide-FOV” mode, to perform an all-sky scan in a time-efficient way at a moderate sensitivity.

## 4. The CTA consortium

CTA is a partnership between the H.E.S.S. and MAGIC collaborations and several European institutes, with recent interests from more institutions world-wide. Activities are coordinated with AGIS (Advanced Gamma-ray Imaging System; cf. [2]), a similar US-based project. The consortium comprises $> 70$ institutes from 17 countries, involving more than 400 scientists.

For the current design phase, CTA is organized in several work packages: Management, Physics, Monte Carlo, Site, Mirror, Telescope, Focal-Plane Instrumentation, Electronics, Atmospheric Transmission and Calibration, Observatory, Data, and Quality Assurance. The telescope design and component prototyping are expected to be completed in 2011 and 2012, respectively. Array prototypes could exist by 2012/13, and the construction of the full array and partial operation could be started in 2014/15.

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