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CTA: The Cherenkov Telescopes Array

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Summary. — The astonishing progress of the ground-based gamma-ray astronomy in the last 10 years (mainly due to high performant instruments such as H.E.S.S., MAGIC and VERITAS) has inspired the scientific community involved to go for the next step in the evolution of the ground-based Imaging Atmospheric Cherenkov Technique. An international Consortium was formed to realize this aim and conceived CTA as an array of Cherenkov telescopes working as an open observatory, covering a wide energy range, with a 10 times enhanced sensitivity and with improved spatial, temporal and energy resolution. At this moment the design stage of CTA has been completed and the project is entering on its preparatory phase in which prototyping and testing are the main tasks before starting the construction foreseen in 2014. In this paper I describe the status of the project, the technical challenges and give an insight on the involved physics.

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1. – Introduction

Very-high energy (VHE) γ-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 γ-rays sources are active galactic nuclei (AGN), particularly blazars and radio-galaxies, gamma-rays bursts and starburst galaxies.

Ground-based gamma-ray astronomy, based on the Imaging Atmospheric Cherenkov Technique, has already demonstrated to be a mature scientific technique to probe non-thermal phenomena in the Universe. Upon reaching the Earth's atmosphere, VHE γ-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. A sizeable fraction of the charged secondary shower particles, mostly electrons and positrons

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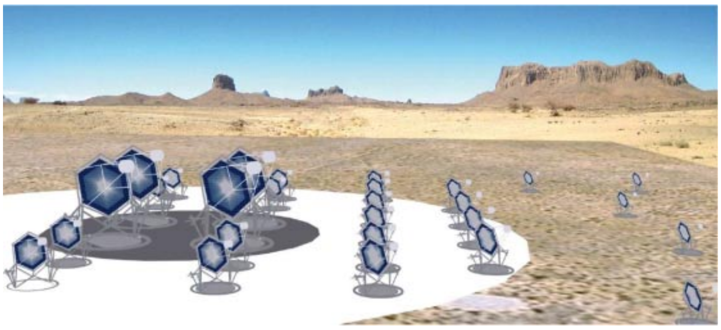

Fig. 1. – Possible layout of the composite CTA southern observatory. The area covered amounts from 1 to 10 km^2. This particular configuration corresponds to four Large Size Telescopes (LST) at the center of the array surrounded by about thirty Middle Size Telescopes (MST) and an extended crown of Small Size Telescopes (SST).

in the shower core, move with ultra-relativistic speed and emit Cherenkov light. This radiation is mainly concentrated in the near UV and optical band and therefore passes mostly unattenuated to the ground. Imaging atmospheric Cherenkov telescopes (IACTs) reflect the Cherenkov light onto multi-pixel cameras that record the shower images.

2. – State of art of the gamma-ray astronomy

The field of ground-based gamma-ray astronomy has been impulsed by the work of the Whipple Collaboration, which successfully discovered the first source of TeV gamma-rays (the Crab Nebula) in 1989—more than 20 years ago. Meanwhile, results from the latest generations of telescopes have revealed a rich sky with different classes of objects emitting gamma-rays in this energy regime [1]. More than 100 TeV sources are known so far, with energy spectra reconstructed from about 100 GeV up to almost 100 TeV. These results were obtained basically with the world largest ground-based IACTs: H.E.S.S., MAGIC and VERITAS [2]. About 60% of the sources are galactic and the rest are mostly AGNs.

At lower energies, in the GeV domain, the launch of a new generation of gamma-ray telescopes (like AGILE [3] in orbit since 2007 and Fermi GST [4], launched in 2008) has opened a new era in gamma-ray discoveries. The Large Area Telescope (LAT), the main instrument onboard Fermi [5], is sensitive to gamma-rays with energies in the range from 20 MeV to about 100 GeV. In the first year of operation, more than 1400 bright sources have been already discovered by Fermi/LAT, producing a bunch of high-quality scientific work.

3. – CTA: a new science infrastructure

CTA is formed by two large arrays of Cherenkov telescopes of different sizes, based on proven technology and deployed on an unprecedented scale. See fig. 1 for an artistic view of the array configuration. It was conceived as a new facility, with capabilities well beyond the existing instruments such as H.E.S.S., MAGIC or VERITAS and their possible upgrades.

This project unites the main research groups in this field in a common strategy, resulting in an unprecedented convergence of efforts, human resources, and know-how. The Consortium is composed nowadays of 25 countries and more than 100 institutions are implicated. Recently, the US AGIS (Advanced Gamma-ray Imaging System) Collaboration has joined CTA raising the number of scientists to more than 700. CTA will, for the first time in this field, provide open access via targeted observation proposals (besides the schedule sky scans) and generate large amounts of public data, accessible using Virtual Observatory tools. CTA aims to become a cornerstone in a networked multi-wavelength, multi-messenger exploration of the high-energy non-thermal universe.

3˙1. *Science motivation.* – CTA science prospectives are wide (for more detailed discussion see [6] and [7]), but they are based on three cornerstones:

- The origin of cosmic rays and their role in the Universe. Basically, the standard paradigm says that galactic cosmic rays are accelerated in shocks generated by supernova explosions. Even though gamma-ray emission is detected from a growing number of SNR, the nature of the underlaying processes is not yet wholly understood. Furthermore, to reach energies of several 10^{15} eV for the CRs, a SNR PeVatron would be needed and none has yet been detected. The deep CTA survey of the Galactic plane should unveil a handful of PeVatrons (~ 25 expected at TeV energies) thought to exist in our Galaxy. CTA will provide also the possibility to make population studies of other types of CRs accelerators candidates as PWNe (~ 100 expected), pulsars and binaries (almost the same number expected). The impact of the accelerated particles on their environment (via the emission from particle interactions with the interstellar medium and radiation fields) will be studied as CTA will enable detailed mappings of VHE emission around potential CR accelerators.

- The nature and variety of particle acceleration around black holes. Objects of interest include blazars, radio galaxies and other classes of AGN that can potentially be studied in high-energy gamma-rays. The fact that CTA will be able to detect a large number of these objects enables population studies which will be a major step forward in this area. CTA will be also able to probe variability time scales well below minutes, putting constraints on acceleration and cooling times, instability growth rates, and the time evolution of shocks and turbulences in these types of sources. Last but not least, CTA will allow us to resolve the outer and inner kpc jet structure of nearby radio galaxies, enabling to spatially pin down the site of the emission. A detailed study of the Extragalactic Background Light (EBL), and the emission from Galaxy clusters and Gamma Ray Burst (GRB) will be also possible by means of CTA.

- Physics beyond the horizon. It is difficult to speculate about the unknown, and definitely we cannot accurately predict how much CTA will unveil about any physics that is beyond our standard model of the world. Gamma-rays, however, hold the potential to reveal properties of the elementary particles that make up our Universe because photonic signatures of particle interactions, decays and annihilations show up in this energy range. Another domain of fundamental physics for which CTA may provide important constraints is the validation of Lorentz invariance. Some theories of quantum gravity predict violation of Lorentz invariance which would manifest as an energy dependence of the speed of light. CTA may provide potentially more stringent constraints from precise timing of AGN flares.

3˙2. *What "unprecedented" performance means.* – CTA will improve the state of the knowledge in astronomy at the highest energies of the electromagnetic spectrum in a num-

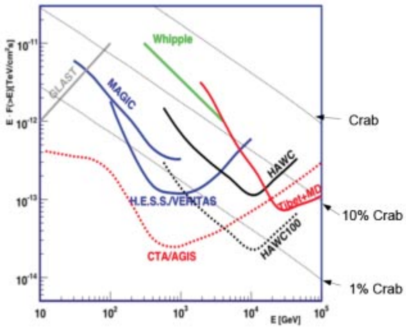

Fig. 2. – Integral sensitivity for a Crab-like spectrum for several current IACT and expected for CTA/AGIS (5σ, 50 h) and Fermi/GLAST (5σ, 1 y).1 Crab Unit $= 1.5 \times 10^3$ $(E/\text{GeV})^{2.58}$ cm^{-2} s^{-1} TeV^{-1} [8].

ber of decisive areas. This observatory aims to provide full-sky view, from a southern and a northern site, with unprecendented sensitivity, spectral coverage, angular and timing resolution, combined with a high degree of flexibility of operation.

– CTA will be about a factor of 10 more sensitive than any existing instrument. It will therefore allow detection and in-depth study of large samples of known source types. It will give the possibility to explore a wide range of classes of suspected gamma-ray emitters beyond the sensitivity of current instruments, and it will be sensitive to new phenomena. See fig. 2.

– CTA is aiming to cover, with a single facility, three to four orders of magnitude in energy range. This will enable (together with lower statical errors and improved precision) astrophysicists to distinguish between hypothesis as the hadronic or leptonique origin of VHE emission in different scenarios. If we also combine CTA with Fermi observations we could achieve a seamless coverage of more than seven orders of magnitude.

– Thanks to the possibility of reconstruct showers from images taken by several telescopes, CTA can reach angular resolutions in the arc-minute range, a factor of 5 better than the typical values for current instruments.

– With its large detection area, CTA will resolve flaring and time-variable emission on sub-minute time scales, which are currently not accessible. CTA will also enable access to (quasi-) periodic phenomena such as emission from inner stable orbits around black holes or from pulsars.

– Consisting of a large number of individual telescopes, CTA can be operated in a wide range of configurations, allowing on the one hand the in-depth study of individual objects with unprecedented sensitivity, and on the other hand the simultaneous monitoring of tens of potentially flaring objects, and any combination in between.

– A consequence of this flexibility is the dramatically enhanced survey capability of CTA. Groups of telescopes can point at adjacent fields in the sky, with their fields of view overlapping, providing an increase of sky area surveyed per unit time by an order of magnitude, and for the first time enabling a full-sky survey at high sensitivity.

3˙3. *Technical challenges*. – In order to cover the large energy range CTA proposes to study (from a few tens of GeV to above 100 TeV), three sizes of telescope are needed. The current baseline design consists of three single-mirror telescopes placed in different configurations and covering areas related to the desired sensitivity (see fig. 1: SST (Small Size Telescopes of 5–8 m diameter); MST (Medium Size Telescopes of 10–12 m diameter); and LST (Large Size Telescopes of 20–30 m diameter)).

Few LSTs should observe the sub-100 GeV photons thanks to their large reflective area. They will have probably a parabolic shape to keep the time spread of showers small. To avoid the intrinsic optical aberrations due to this profile, LSTs will probably have limited Field of View (FOV $\sim$ 4 or 5°). This implies a large telescope focal length to diameter ratio ($f/d \geq 1.2$) which will be translated on the technical challenge of displacing the camera at more than 28 m from the reflector. Several tens of MSTs will perform the bulk TeV search. The well-proven experience of H.E.S.S., MAGIC and VERITAS Collaboration will be used on these telescopes design. The main goal is to reduce the costs and maintenance activities. They will constitute the core of the array and will also perform the fundamental task of vetoing the LST triggers to reduce the hadronic background. Several different designs are currently taken into account and the construction of the first prototypes is expected next year. Finally, several tens of SSTs will complete the array to perform the super-TeV search. They shall be very simple in construction and should contribute to a small percentage of costs of the full array. In parallel with the prototyping of a single-mirror MST, the design of a Schwarzschild-Couder telescope from AGIS is also undergoing [9]. These telescopes are going to be distributed in between and around the core array of MSTs covering multi-km^2 area.

A major effort is currently concentrated on the telescope design, the mirror facets development and the electronic and focal plane instrumentation. Different projects for SSTs, MSTs and LSTs are under design at several institutes to stimulate competition and technological development. Mirrors constitute an important challenge because they contribute to a sizeable part of the costs. Most of the work is oriented to build fast assembling and reliable mirrors with reduced optical degradation with time. A review of the different techniques under study can be found in [10]. The focal plane instrumentation also represents a challenge in technology and cost. The efficiency of the collection of Cherenkov photons and their conversion to photoelectrons in the photo-sensor must therefore be improved. Enlarging the energy range requires appropriate electronics with a sufficiently large dynamic range. Sophisticated application-specific integrated circuits (ASICs) for equipping the front-end part of the readout chain are under study. Several analogue memories have been proposed: the DRS chip [11], used in MAGIC, the TARGET chip [12] and the new NECTAr chip [13], based on the SAM chip used in H.E.S.S. In parallel, low-power, low-cost and modest-speeds FADCs are being studied for the MST and SST telescopes. For the photodetection system, the current baseline design envisages the use of high conversion efficiency PMTs. Studies are ongoing also on GaAsP hybrid photon detectors (HPD) and Geiger avalanche photon detectors (GAPD) [14].

4. – The Consortium

The CTA Consortium has began as a partnership between the H.E.S.S. and MAGIC Collaborations plus several European institutes. The last few years, world-wide institutions have also joined the Consortium and the present activities are combined with the US AGIS (Advanced Gamma-ray Imaging System) scientists. The Consortium hosts already around 25 countries and more than 700 scientists. For the finishing design phase, CTA was 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 CTA project recently entered the preparatory phase, funded by the European Commission under the Seventh Framework Programme (FP7), which will address a number of crucial prerequisites for the approval, construction and operation of CTA. This phase will last for 3 years and will deliver a complete and detailed implementation plan for the CTA infrastructure. Array deployment may then start from 2013 on, provided that funding is secured.

5. – Observatory future operation

The majority of studies will be based on observations of specific astronomical sources. The scientific programme will hence be steered by proposals to conduct measurements of specific objects. CTA will be operated as an open observatory so, beyond a base programme, observations will be conducted according to observing proposals selected for scientific excellence by peer-review among suggestions received from the countries supporting the Observatory. Besides that, a significant number of proposals from scientists working in institutions outside the CTA Consortium will be taken into account. All data obtained by the observatory will be made available in an archive that is accessible to scientists from the astronomy community. CTA observatory operations will involve proposal handling and evaluation, managing observations and data-flow, and maintenance. The work would be conducted in a central location or in decentralised units with a coordinating office.

6. – Conclusions

The CTA observatory is the logical next step in the exploration of the high-energy Universe and will promote VHE observations to a public tool for modern astronomy. CTA will explore the VHE domain from several tens of GeV up to more than 10 TeV with unprecedented sensitivity and angular resolution, enabling a comprehensive understanding of cosmic particle acceleration physics at various scales, distances and time scales. CTA has recently received substantial funding from the European Community, for the preparation for construction and operation, and from national funding agencies, for development and prototyping. In about 5 years from now, CTA will produce its first results starting the next era on the VHE gamma-rays astronomy.

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