The Cerenkov Telescope Array
Project Status

The CTA Consortium(*), represented by E. Bissaldi(1)(2)

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Summary. — The Cherenkov Telescope Array (CTA) represents the next generation ground-based observatory for gamma-ray astronomy at very-high energies. It will be capable of detecting gamma rays in the energy range from 20 GeV to more than 300 TeV with unprecedented precision in energy and directional reconstruction. CTA will be located in the northern hemisphere at La Palma, Spain, and in the southern hemisphere at Paranal, Chile, and will comprise more than 100 telescopes of three different types.
CTA will be one of the largest astronomical infrastuctures in the world with open data access and it will address questions in astronomy, astrophysics and fundamental physics in the next decades. In this contribution we will present the status of the CTA construction, discuss the telescope prototypes, highlight the scientific perspectives and the instrument performances.

1. – Introduction

Ground-based gamma-ray astronomy is a novel field with enormous scientific potential. Since the first successful measurement of an astrophysical source at TeV energies, with the detection of a signal from the Crab Nebula by the Whipple Telescope in 1989 (exactly 30 years ago) [1], both the imaging atmospheric Cherenkov technique (IACT) and its associated telescopes and instrumentation have greatly evolved. Today, the field is an established discipline of observational astrophysics, enjoying almost 200 detected sources(1) in its catalog, and discoveries which have generated great impact in wider domains of physics and astrophysics over the past decade or so. Most of these discoveries have been made by the major ground-based IACTs, H.E.S.S., MAGIC, and VERITAS,

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(*) see `https://www.cta-observatory.org/consortium\_authors/authors\_2019\_06.html` for full author list
(1) `https://tevcat.uchicago.edu/`

that have been joined in recent years by the air shower array HAWC. Important contributions have also come from the space instruments Fermi-LAT and AGILE.

CTA will be the major global observatory for very-high energy (VHE) gamma-ray astronomy over the next decade and beyond. Covering photon energies from 20 GeV to 300 TeV, CTA will improve on all aspects with respect to current IACT instruments, allowing detailed imaging of a large number of gamma-ray sources, and being a powerful instrument for time-domain astrophysics. CTA will transform our understanding of the VHE universe and will address important questions in fundamental physics. Compared to the existing IACTs, CTA will: 1) cover a wider energy range, 2) have a significantly larger field-of-view, and 3) achieve up to an order of magnitude improvement in sensitivity. Angular resolution and energy resolution will also be improved and full-sky coverage will be ensured by arrays in both the southern and northern hemispheres. CTA will also be the first open observatory to operate in the VHE waveband, with approximately 50% of the observing time set aside for guest observer proposals and all high-level data available to the public after a proprietary period (typically one year). The plan is to operate the observatory for an envisaged lifetime of 30 years, with major upgrades expected on a timescale of 10 to 15 years.

CTA has been in development for more than a decade. The concept was originated by the CTA Consortium, currently consisting of around 1,420 scientists from more than 200 institutes in 31 countries. The Consortium has also developed the core science program and has led the prototyping of telescope hardware [2]. The CTA Observatory gGmbH (CTAO gGmbH) is the legal entity for CTA in the preparation of the implementation of the CTA Observatory. The CTAO works in close cooperation with the CTA Consortium and is governed by the CTAO Council. Given a project the size and scope of CTA, international partnerships and good cooperation between the different stakeholders involved in the project (e.g. funding agencies, national laboratories, and scientific communities) are required. CTA was included in the 2008 roadmap of the European Strategy Forum on Research Infrastructures (ESFRI) and promoted to a Landmark project in 2018. It is one of the Magnificent Seven of the European strategy for astroparticle physics published by ASPERA, and highly ranked in the strategic plan for European astronomy of ASTRONET. In addition CTA is a recommended project for the next decade in the US National Academies of Sciences Decadal Review.

2. – CTA Array Sites and Office Locations

Two Sites are planned for CTA in order to obtain full sky coverage. The southern array site will be near Paranal, in the Atacama Desert, in Chile, while the northern array site will be in Villa de Garafia on the island of La Palma in the Canary Islands. CTA entered detailed hosting contract negotiations with the European Southern Observatory (ESO) for the southern array site and the Instituto de Astrofisica de Canarias (IAC) for the northern array site back in 2015. Hosting agreements were then signed with IAC in September 2016 and with ESO in December 2018. Fig. 1 illustrates a potential layout of the telescope arrays in both the northern and southern hemispheres.

CTA's southern hemisphere site is less than 10 km southeast of the ESO's existing Paranal Observatory. The plan is for the site to host a very large array of telescopes, spanning the entire energy range of CTA and comprising all three classes of CTA telescopes spread over 4 square kilometers: four Large-Sized Telescopes (LSTs) reaching the low-energy sensitivity of CTA, 25 Medium-Sized Telescopes (MSTs) to cover the core energy range and 70 Small-Sized Telescopes to capture the highest energy gamma rays.

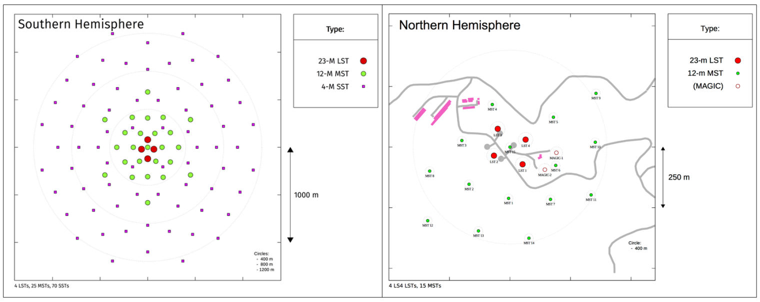

Fig. 1. – Potential layout of the CTA telescope arrays in the southern (left panel) and northern (right panel) hemispheres.

CTA's northern hemisphere site is located on the existing site of the IAC's Observatorio del Roque de los Muchachos at 2,200 metres a.s.l. on La Palma, where the MAGIC telescopes, as well as a wide variety of optical telescopes are operative. The CTA array will be more limited in size and will focus on CTA's low- and mid-energy ranges from 20 GeV to 20 TeV thanks to four LSTs and 15 MSTs. No SST will be hosted in the northern CTA site. An LST prototype (LST-1)(2) is currently under construction on the La Palma site. LST-1 is intended to become the first of the four LSTs on the CTA-North site. Its inauguration took place on October 10, 2018, while first light was achieved on the night of December 14-15, 2018. As any other technical delivery in the large, multinational CTA project, the LST-1 will need to undergo a critical design review to verify that the design complies with CTA science goals, operational needs, safety standards, etc. before it is formally accepted by CTAO.

The CTA Headquarters are hosted in Bologna (Italy) since early 2017. They represent the central office responsible for the overall administration of Observatory operations. In the future, they will provide technical coordination and support, and the main administrative services for the governing bodies and users of the Observatory. The Science Data Management Centre (SDMC) is currently under construction at the Deutsches Elektronen-Synchrotron (DESY) campus in Zeuthen (Berlin, Germany). It will coordinate science operations and make CTA's science products available to the worldwide community. The SDMC will manage CTA's science coordination including software maintenance and data processing for the Observatory, which is expected to generate approximately 100 PB of data by the year 2030.

3. – CTA Telescopes

The full CTA instrumentation, distributed over both array sites, will comprise 118 telescopes. In total, 8 LSTs, 40 MSTs and 70 SSTs are planned to be build over the next years. While the individual telescopes may vary in size and design, CTA telescopes will be constructed and will perform similarly. Each telescope will have a mount that allows it to rapidly point towards targets and will be comprised of a large segmented mirror to reflect the Cherenkov light to a high-speed camera that can digitize and record the image of the shower.

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(2) `http://www.lst1.iac.es/`

LSTs – Because gamma rays with low energies produce only a small amount of Cherenkov light, telescopes with large mirrors are required to capture the images. Four LSTs will be arranged at the centre of both the northern and the southern hemisphere arrays to cover the low energy sensitivity of CTA between 20 and 150 GeV. The LST is an alt-azimuth telescope [3], and is represented on the right of Fig. 2. Its mirror will be 23 metres in diameter and parabolic in shape. Its camera will use photomultiplier tubes (PMTs) and will have a field of view (FoV) of about 4.5°. The entire structure will weigh around 100 tonnes but will be extremely nimble, with the goal to be able to re-position within 20 seconds. Both the re-positioning speed and the low energy threshold provided by the LSTs are critical for CTA studies of galactic transients, high redshift active galactic nuclei (AGN) and gamma ray bursts (GRBs). The LSTs will expand the science reach to cosmological distances and fainter sources with soft energy spectra.

MSTs – MSTs will have a sensitivity in the core energy range of CTA, from about 150 GeV to 5 TeV [4]. The MST is a modified Davies-Cotton telescope with a reflector diameter of 12 m on a polar mount, and a focal length of 16 m. The MST will have up to 90 hexagonal-shaped mirrors that are aligned with an active mirror control assembly to create a uniform reflector. Each MST will have two different camera designs that use photomultiplier tubes (PMTs). The MST cameras will have a large FoV of about 8°, enabling the MSTs to take rapid surveys of the gamma-ray sky. The two camera designs comprise the "NectarCAM" [5] and the "FlashCAM" [6].

An MST prototype was deployed in Berlin in 2012 and is currently undergoing performance testing [7]. The main purpose of the prototype is to validate the design of the individual components, test the interfaces between the mating assemblies and to define the assembly process of the product. The prototype has a fully functional drive system, cameras for pointing and tracking, sensors designed to record the behavior response of the structure and drive system and a weather station. It is a fully-functioning telescope, without a real telescope camera assembly and its readout. Camera demonstrators were built, tested and validated in parallel by the two camera sub-projects.

A dual-mirrored version of the MST, the Schwarzschild-Couder Telescope (SCT), is proposed as an alternative type of medium telescope [8]. The SCT's two–mirror optical system is designed to better focus the light for greater imaging detail and improved detection of faint sources. The SCTs have improved angular resolution as a result of a smaller point spread function (PSF) and the very large number of camera pixels (>11000), based on silicon photomultipliers (SiPMs), covering approximately 8° FoV. Both the 9.7 m diameter primary and 5.4 m secondary mirrors are segmented and have active alignment. The unique optical support structure is designed to support segmented primary and secondary mirrors as well as the high angular resolution camera. It is designed to provide minimal shadowing, control of stray light and protection from sunlight during daytime parking.

An SCT prototype(3) (pSCT) was build and inaugurated on January 17, 2019 at the Fred Lawrence Whipple Observatory in Arizona (USA). The main goals of the prototype will be to demonstrate the performance of the optical system and gain experience with the optical alignment and operation of the SiPM camera. Both MST prototypes are represented in the middle of Fig. 2.

SSTs – The Small-Sized Telescopes (SSTs) will outnumber all the other telescopes with 70 planned to be spread out over several square kilometers in the southern hemi-

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(3) `https://cta-psct.physics.ucla.edu/`

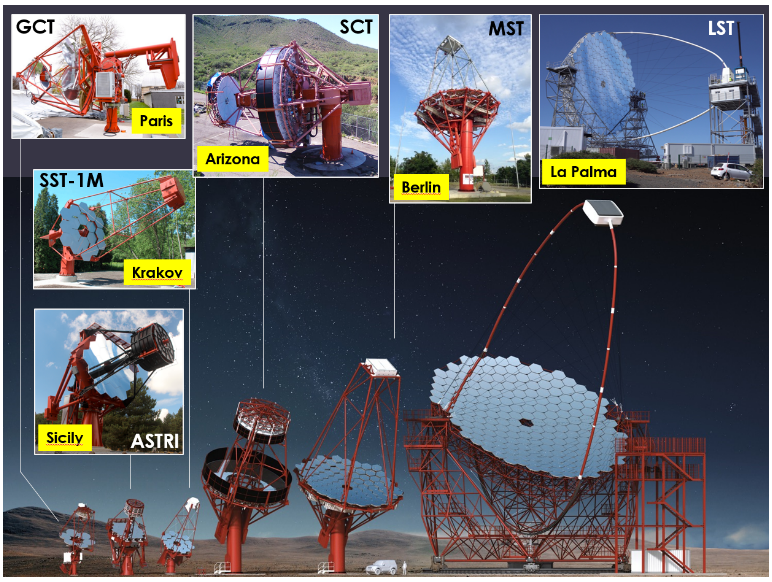

Fig. 2. – Concept drawings and photographs of CTA protoype telescopes, as of 2019.

sphere array only. Since very high-energy gamma-ray showers produce a large amount of Cherenkov light over a large area, 70 SSTs are planned to be spread out over several square kilometers in the southern hemisphere array only. They will be sensitive in the few TeV – 300 TeV energy range.

Three different SST implementations are being prototyped and tested: one single-mirror design, SST-1M(4), and two dual-mirror designs, SST-2M ASTRI(5) and SST-2M GCT(6). In May 2018, it was decided that a single design for the SST will be developed for the observatory. The project manager will work with each of the teams to harmonise the designs into one.

The SST mirror will be about 4 m in diameter and will have a large FoV of about 8-10°. The dual-mirror designs allow excellent imaging across a wide FoV with a short focal length. The resulting small plate scale allows the use of SiPMs, assembled in very compact cameras. The SST-1M also uses silicon sensors, in the form of individual hexagonal pixels equipped with light concentrators (Winston cones). All three SST prototypes are represented on the left of Fig. 2.

4. – CTA science

Recently, the CTA Consortium has published a proposal for a Core Programme of highly motivated observations [2]. With its superior performance, the prospects for CTA combine guaranteed science – the in-depth understanding of known objects and mechanisms – with anticipated detection of new classes of gamma-ray emitters and new

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(4) `http://dpnc.unige.ch/astro/styled/index.html`
(5) `http://www.brera.inaf.it/~astri/wordpress/`
(6) `https://cta.obspm.fr/projet-gct/`

phenomena, and a very significant potential for fundamentally new discoveries. CTA will seek to address questions in and beyond astrophysics which fall under three major themes of study: (1) Understanding the origin and role of relativistic cosmic particles; (2) Probing extreme environments; and (3) Exploring frontiers in physics. The answers to these questions will be searched through the study of following key targets: (a) the Galactic Centre; (b) the Large Magellanic Cloud; (c) the Galactic Plane; (d) Galaxy Clusters; (e) Cosmic Ray PeVatrons; (f) Star-forming systems; (g) AGN; and (h) Transient phenomena.

Unlike current instruments, CTA will be operated as a proposal-driven open observatory. Observations will be carried out by observatory operators, then the data will be calibrated, reduced and, together with analysis tools, made available to the principle investigator in FITS data format. After a proprietary period, data will be made openly available through the CTA data archive. The modes of user access to CTA will be:

- The Guest Observer (GO) Programme: users can obtain access to proprietary observation time, submitting proposals in response to Announcements of Opportunity (AOs);
- The Key Science Projects (KSPs): large programmes that ensure that some of the key science issues for CTA are addressed in a coherent fashion, with a well-defined strategy;
- Director's Discretionary Time (DDT): a small fraction of observation time may be reserved for, e.g., unanticipated targets of opportunity, or outstanding proposals from non-member countries;
- Archive Access: all CTA gamma-ray data will be openly available, after a proprietary period.

During the first phase of operation, observation time will be split between guest observer time and KSPs, such as large-scale surveys aimed at providing legacy data sets.

The Transients KSP in particular will represent an integrated programme that encompasses a variety of multi-wavelength and multi-messenger (MM) alerts, including explosive transients such as GRBs and gravitational wave events, AGN flares, Galactic transients, and high-energy neutrino alerts. Rapid dissemination to the wider community of the VHE properties of transients observed by CTA is an important component of the KSP and will be crucial to strengthen the synergy between CTA and other MM observatories, like the IceCube Neutrino Observatory(7), and the LIGO(8) and Virgo(9) experiments.

5. – CTA performances

CTA will provide very wide energy range and excellent angular resolution and sensitivity in comparison to any existing gamma-ray detector. Energies up to 300 TeV will push CTA beyond the edge of the known electromagnetic spectrum, providing a completely new view of the sky. The performance expected from CTA was obtained from detailed Monte Carlo (MC) simulations of the proposed baseline array layouts for the southern and northern sites [10]. The MC simulations are similar to the ones presented in [11], but using Corsika 6.9, an updated detector model of the CTA telescopes, and

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(7) `https://icecube.wisc.edu/`
(8) `https://www.ligo.org/`
(9) `http://www.virgo-gw.eu/`

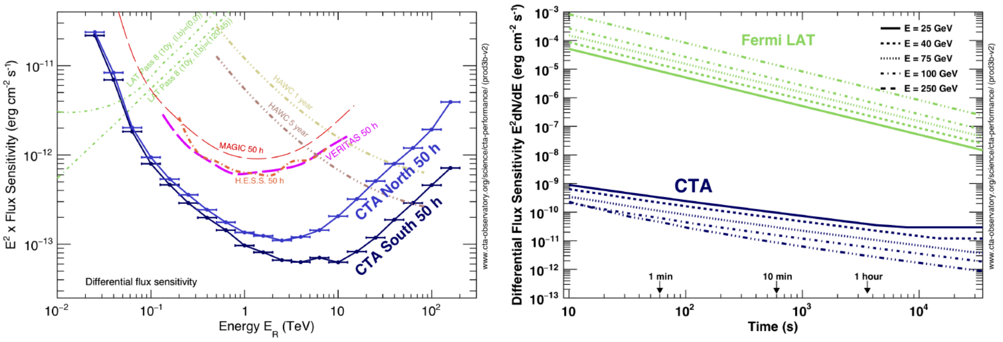

Fig. 3. – On the left: Differential sensitivity for an observation time of 50 hours for the CTA North (blue curve) and South (dark blue curve) array compared to other instruments' sensitivities (Fermi-LAT, H.E.S.S., MAGIC, VERITAS, and HAWC). On the right: Differential flux sensitivity of CTA at selected energies as function of observing time in comparison with Fermi-LAT.

optimized telescope layouts (the so-called 'Production 3b'). Two independent analyses of the MC sample have been carried out, yielding similar results. The analyses are classical ones, based on parametrised shower images, some improvement is expected with the use of more sophisticated techniques fully exploiting pixel-wise information. The IRFs used for the simulations were obtained using up-to-date telescope models and arrays deployed at the selected construction sites.

The left panel of Fig. 3 shows the differential sensitivity, defined as the minimum flux needed by CTA to obtain a 5-standard-deviation detection of a point-like source, calculated in non-overlapping logarithmic energy bins (five per decade). Besides the significant detection, we require at least ten detected gamma rays per energy bin, and a signal/background ratio of at least 1/20. The analysis cuts in each bin have been optimised to achieve the best flux sensitivity to point-like sources. The optimal cut values depend on the duration of the observation. Here, the IRF is provided for an observation time of 50 hours and the sensitivity curves are compared to other currently-operating instrument like Fermi-LAT, H.E.S.S., MAGIC and HAWC.

The differential flux sensitivity of CTA at selected energies as function of observing time in comparison with Fermi-LAT is shown in the right panel of Fig. 3. The differential flux sensitivity is defined as the minimum flux needed to obtain a 5-standard-deviation detection from a point-like gamma-ray source, calculated for energy bins of a width of 0.2 decades. An additional constraint of a minimum of 10 excess counts is applied. Note that especially for exposures longer than several hours, the restrictions on observability of a transient object are much stricter for CTA than for the Fermi LAT. CTA will be able to observe objects above 20° elevation during dark sky conditions. The differential flux sensitivity shown here are for observations near 70° elevation angles.

These performance parameters are valid for a source located close to the centre of the CTA FoV. The differential sensitivity curves for a point-like source at increasing angular distances from the centre of the FoV are presented in Fig. 4 for both arrays. The radius of the FoV region in which the sensitivity is within a factor 2 of the one at the centre is around 2° near the CTA threshold, and >3° above a few 100 GeV.

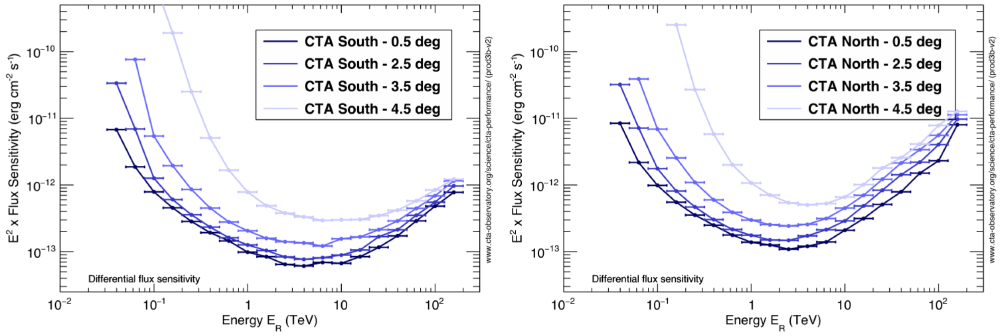

Fig. 4. – Differential sensitivity curves for a point-like source at increasing angular distances from the centre of the FoV for the South (left panel) and North array (right panel).

6. – Conclusions

The project to build CTA is well-advanced: all prototype telescopes (MST prototype and all three proposed designs of the SST) have achieved 'first light' before 2018. The LST-1 and pSCT prototypes were inaugurated in October 2018 and in January 2019, respectively, and had their 'first light' shortly thereafter. Finally, the agreements needed for CTA's southern hemisphere array to be hosted near ESO's Paranal Observatory in Chile were reached in December 2018. In the next years, CTA will be an important member of the suite of experiments and observatories participating in the expanding areas of multi-wavelength and multi-messenger astronomy.

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