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The Cherenkov Telescope Array: Exploring the Very-high-energy Sky from ESO's Paranal Site

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The Cherenkov Telescope Array (CTA) is a next-generation observatory for ground-based very-high-energy gamma-ray astronomy, using the imaging atmospheric Cherenkov technique to detect and reconstruct gamma-ray induced air showers. The CTA project is planning to deploy 19 telescopes on its northern La Palma site, and 99 telescopes on its southern site at Paranal, covering the 20 GeV to 300 TeV energy domain and offering vastly improved performance compared to currently operating Cherenkov telescopes. The combination of three different telescope sizes (23-, 12- and 4-metre) allows cost-effective coverage of the wide energy range. CTA will be operated as a user facility, dividing observation time between a guest observer programme and large Key Science Projects (KSPs), and the data will be made public after a one-year proprietary period. The history of the project, the implementation of the arrays, and some of the major science goals and KSPs, are briefly summarised.

Introduction

In the coming years, up to 99 of the Cherenkov Telescope Array (CTA) telescopes with dish sizes between 4 metres and 23 metres will be installed at the Paranal site, in the flat areas east of route B-710 (Figure 1). CTA will be the premier observatory for imaging the Universe at very high energies (VHE), covering the electromagnetic spectrum at energies from 10's of GeV to 100's of TeV. More information can be found in Acharya et al. (2013) and on the CTA website[1].

CTA employs Imaging Atmospheric Cherenkov Telescopes (IACTs) — large telescopes with ultraviolet–optical reflecting mirrors that focus flashes of Cherenkov light produced by γ-ray initiated atmospheric particle cascades (air showers) onto nanosecond-response cameras (Figure 2). Compared to space-based detectors that are limited to detection areas of around a square metre, Cherenkov telescopes use the Earth's atmosphere as a detection medium and provide detection areas in excess of 10^5 square metres, capable of coping with the very low flux of VHE γ-rays. Today's instruments use arrays of IACTs to image a cascade from different viewing angles, improving angular and energy

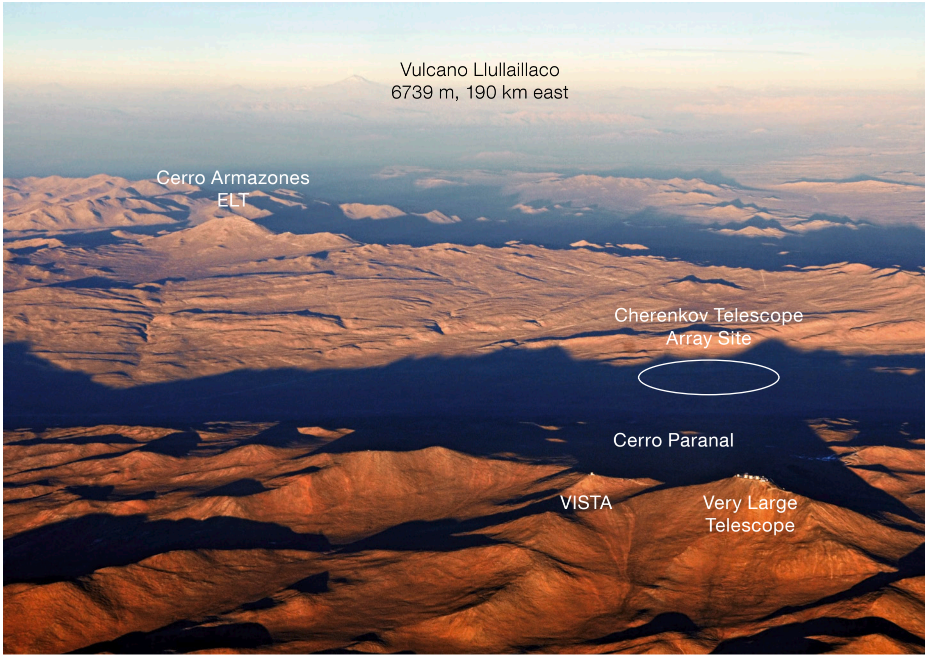


Figure 1. The location of the CTA southern array, in the valley between Cerro Paranal and Cerro Armazones.

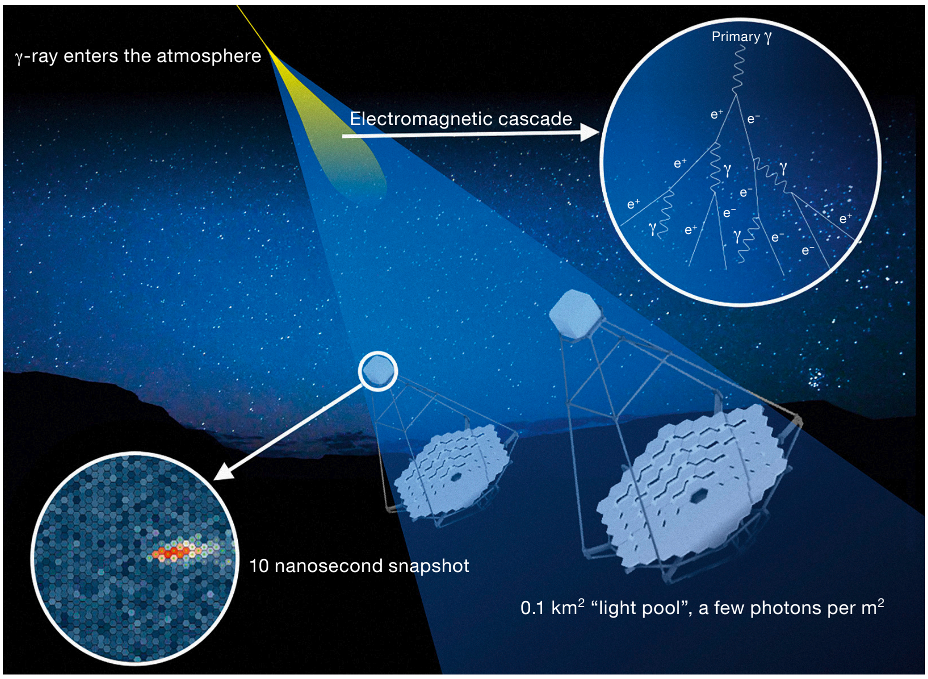


Figure 2. Detection of primary γ-rays using the Cherenkov light from the γ-ray induced air showers. A telescope will "see" the γ-ray if it is located in the ~250-metre diameter Cherenkov light pool. The different views of the air shower provided by multiple telescopes allow reconstruction of the shower geometry and hence of the direction of the incident γ-ray.

resolution of the γ-rays, as well as increasing the rejection of similar cascades initiated by cosmic-ray particles.

Ground-based γ-ray astronomy at very high energies is a young branch of astronomy that has developed very rapidly since the detection of the first cosmic VHE source in 1989 by the Whipple telescope (Hillas, 2013). The initial concepts for CTA as the first major open observatory for this waveband were formulated in 2005, motivated by the success of existing IACTs, such as the High Energy Stereoscopic System (HESS), the Major Atmospheric Gamma Imaging Cherenkov (MAGIC) and the Very Energetic Radiation Imaging Telescope Array System (VERITAS). These instruments have demonstrated that observations at these extreme energies are not only technically viable and competitive in terms of precision and depth, but also scientifically rewarding and with broad scientific impact. Their success has resulted in a rapid growth in the interested scientific community. Topics addressed with γ-ray observations include[2]:
(i) The origin and role of relativistic cosmic particles. Particles in our Galaxy and beyond are traced by the γ-rays they emit when interacting with gas or with radiation fields; this allows us to address questions like: what are the sites of high-energy particle acceleration in the Universe? what are the mechanisms for cosmic particle acceleration? and what role do accelerated particles play in feedback mechanisms related to star formation and galaxy evolution?
(ii) Probing extreme environments, for example, the physical processes that are at work close to neutron stars and black holes and the characteristics of relativistic jets, winds and explosions. γ-ray interactions can also be used to explore the radiation fields and magnetic fields in extreme cosmic voids, and their evolution over cosmic time.
(iii) Exploring frontiers in fundamental physics, such as: searching for dark matter particles annihilating into γ-rays, allowing us to probe the nature and distribution of dark matter; investigating mechanisms affecting photon propagation over cosmological distance, such as quantum gravitational effects causing tiny variations of the speed of light with photon energy; and photon-axion oscillations in cosmic magnetic fields.

CTA is envisaged as a general-purpose observatory for the VHE waveband, building on the techniques and technologies demonstrated by the currently operating IACTs, and improving on essentially all aspects of their performance. CTA will be the first truly open VHE observatory, providing accessible data products and support services to a wide scientific community. It will exploit large arrays of Cherenkov telescopes on two sites to provide all-sky coverage, broad energy coverage and unprecedented precision.

Some history

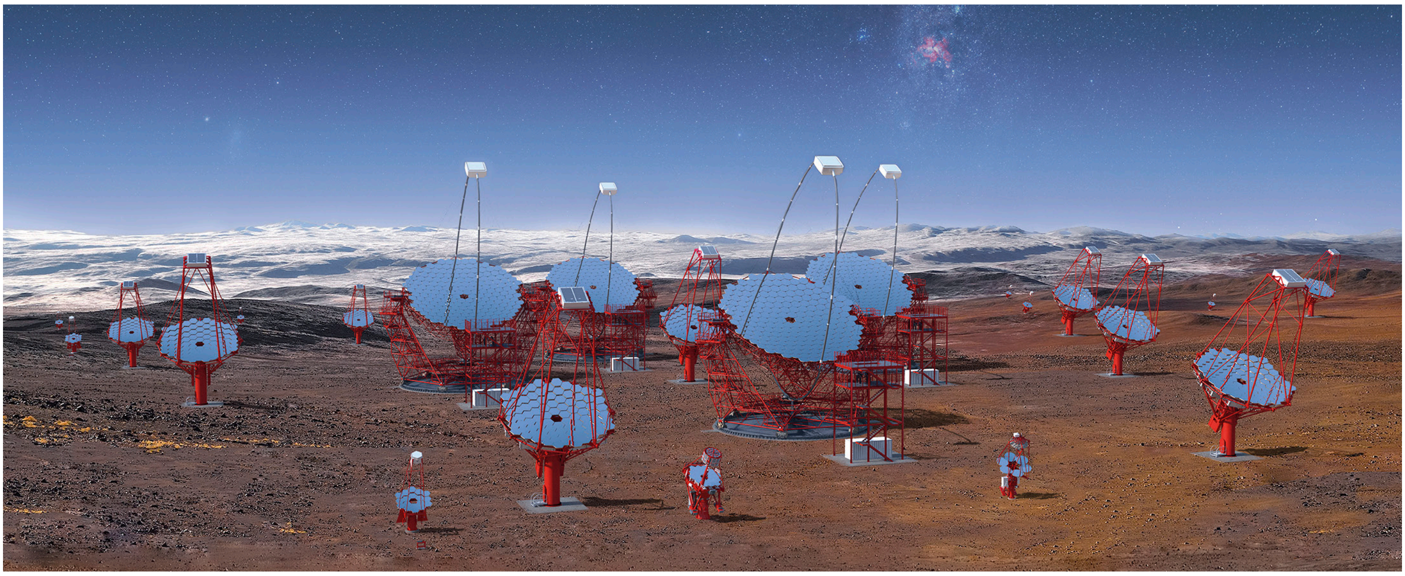
The CTA project was proposed and developed by the CTA Consortium (CTAC) that was formally established in 2008. The Consortium has now grown to over 1300 scientists and engineers from more than 200 institutes in 32 countries, involved in the design and prototyping of the telescopes and the associated auxiliary instruments and software, as well as in the characterisation of sites for the telescopes. Of ESO's 16 Member States, 13 are also represented in the CTA Consortium. In 2014, the CTA Observatory (CTAO) gGmbH was founded in Heidelberg, to provide a legal framework for the operation of the CTA Project Office, and for the contracts towards implementation of CTA. The CTAO gGmbH is governed by its Council of representatives of the shareholders from Austria, the Czech Republic, France, Germany, Italy, Japan, Spain, Switzerland and the United Kingdom, and from the Netherlands and South Africa as Associate Members. Work towards CTA was and is supported by the European Union under FP7 and H2020; since 2008, CTA is listed in the roadmap of the European Strategy Forum on Research Infrastructures (ESFRI).

A comprehensive programme of site search and site evaluation was conducted by the CTA Consortium from 2010 to 2013, resulting in a shortlist of sites and detailed input to a Site Selection Committee appointed by the CTA Resource Board (RB) of agency representatives (the RB preceded the CTAO Council). In July 2015, the RB decided to enter into detailed contract negotiations around hosting the southern array on the Paranal site in Chile and the northern array at the Instituto de Astrofisica de Canarias (IAC), Roque de los Muchachos Observatory in La Palma, Spain. The hosting agreement with IAC was signed in September 2016; the hosting agreement with ESO was approved in late 2016 by both the CTAO and ESO Councils. It is envisaged that ESO will become a scientific partner in CTA, expanding ESO's portfolio of wavebands and leveraging the scientific and operational synergies with its optical telescopes and the Atacama Millimeter/submillimeter Array (ALMA). ESO will operate the southern telescope array for CTAO and will receive observation time on CTA's arrays as well as voting rights in the CTAO's governing bodies. Also in 2016, the decision was taken to locate the CTA Headquarters at Bologna in Italy; the Science Data Management Centre will be hosted at Zeuthen near Berlin, Germany.

The full economic cost for implementing CTA is estimated at 400 M€; however, even with a reduced number of telescopes, CTA will provide a state-of-the-art astronomical facility, and a funding level of 250 M€ was established as the threshold for starting the implementation. Signature of a Memorandum of Understanding (MoU) towards construction and operation is underway and currently accounts for over 200 M€; the 250 M€ threshold should be reached in the near future.

The telescope arrays

In all aspects, CTA represents a significant step forward with respect to current instruments, and the combined effect is expected to be transformational for the field. For example, the improved γ-ray collection area, the background rejection power and the larger field of view increase the survey speed of CTA by a factor of several hundred with respect to current instruments. Sensitivity to point sources of γ-rays will be up to an order of magnitude higher than current instruments. The angular resolution of CTA will approach one arcminute at high energies — the best resolution of any instrument operat-



CTA/Gabriel Pérez Diaz/IAC/SMM/ESO/B.Tafreshi

ing above the X-ray band — allowing detailed imaging of a large number of γ-ray sources.

CTA will take the IACT technique to its next level, by deploying extended arrays of Cherenkov telescopes (Figures 3 and 4). In the current arrays, with at most five telescopes spaced by about 100 metres (compared to the ~250-metre diameter of the Cherenkov light pool), the bulk of the recorded air showers have impact points outside the footprint of the array, implying that usually only two telescopes record the shower, and that the angle between stereoscopic views of the cascade is modest, impacting the spatial reconstruction. CTA will for the first time deploy telescopes across areas that exceed the size of the Cherenkov light pool, resulting in:
- a dramatically increased rate of air showers contained within the footprint of the telescope array;
- an increased number of views of the air shower from different viewing angles, improving both the reconstruction of air-shower parameters and the rejection of cosmic-ray induced air showers as the major source of sensitivity-limiting background;
- a lower effective energy threshold since, for contained showers, there are always telescopes in the region of highest density of Cherenkov light.

For wide usable energy coverage, it is desirable for the effective γ-ray detection area to increase with γ-ray energy, compensating for the rapid drop of γ-ray flux with increasing energy (for typical sources, the γ-ray flux drops with energy, E, like $dN_\gamma/dE \sim E^{-2}$ or faster). Hence, rather than deploying one type of Cherenkov telescope on a regular grid, the CTA arrays use a graded approach:
- The lowest energies are covered by an arrangement of four Large-Sized Telescopes (LSTs, of 23-metre dish diameter), capable of detecting γ-rays as low as 20 GeV.
- The 0.1 to 10 TeV range is covered by larger arrays of 25 (south) and 15 (north) Medium-Sized Telescopes (12-metre MSTs).
- The highest energy γ-rays are detected by a multi-kilometre square array of 70 Small-Sized Telescopes (4-metre SSTs) in the south.

Figure 3. (Above) Artist's rendering of the southern CTA site.

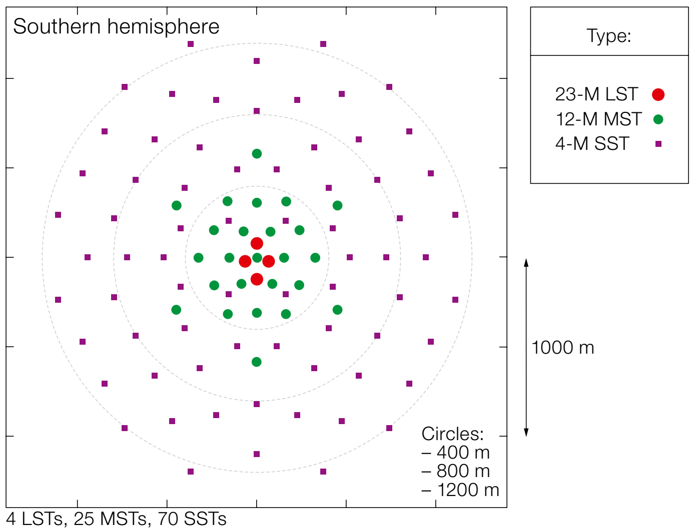


Figure 4. (Right) Layout of the southern telescope array, combining 4 LSTs, 25 MSTs and 70 SSTs.

The small telescopes are only foreseen for the southern array (Figure 4), since the highest energies are most relevant for the study of Galactic sources. The use of three different sizes of telescope proved to be the most cost-effective solution, and it allows each telescope type to be optimised for a specific energy range. The detailed specifications of the telescopes and the layout of the CTA arrays are the result of a multi-step optimisation process, extending over several years and using 10's of millions of CPU-hours

Telescope	Large	Medium		Small		
	LST	MST	SCT	SST-1M	ASTRI SST-2M	GCT SST-2M
Number North array	4	15	TBD		0	
Number South array	4	25	TBD		70	
Optics						
Optics	Parabolic mirror	Modified Davies-Cotton	Schwarzschild-Couder	Davies-Cotton	Schwarzschild-Couder	Schwarzschild-Couder
Primary mirror diameter (m)	23	12	9.7	4	4	4
Secondary mirror diameter (m)	—	—	5.4	—	1.8	2
Eff. mirror area after shadowing (m^2)	370	90	40	7.4	6	6
Focal length (m)	28	16	5.6	5.6	2.1	2.3
Focal plane instrumentation						
Photo sensor	PMT	PMT	Silicon	Silicon	Silicon	Silicon
Pixel size (degr.), shape	0.10, hex	0.18, hex	0.07, square	0.24, hex	0.17, square	0.15–0.2, square
Field of view (degr.)	4.5	7.7/8.0	8.0	9.1	9.6	8.5–9.2
Number of pixels	1855	1764/1855	11328	1296	1984	2048
Signal sampling rate	GHz	250 MHz/GHz	GHz	250 MHz	S&H	GHz
Structure						
Mount	alz-az, on circular rail	alt-az positioner	alt-az positioner	alt-az positioner	alt-az positioner	alt-az positioner
Structural material	CFRP/steel	steel	steel	steel	steel	steel
Weight (full telescope, tons)	100	85	~85	9	15	8
Max. time for repositioning (s)	20	90	90	60	80	60

Table 1. Parameters of the different CTA telescopes currently under prototyping. For details of telescope technology, see Gamma, 2016[3].

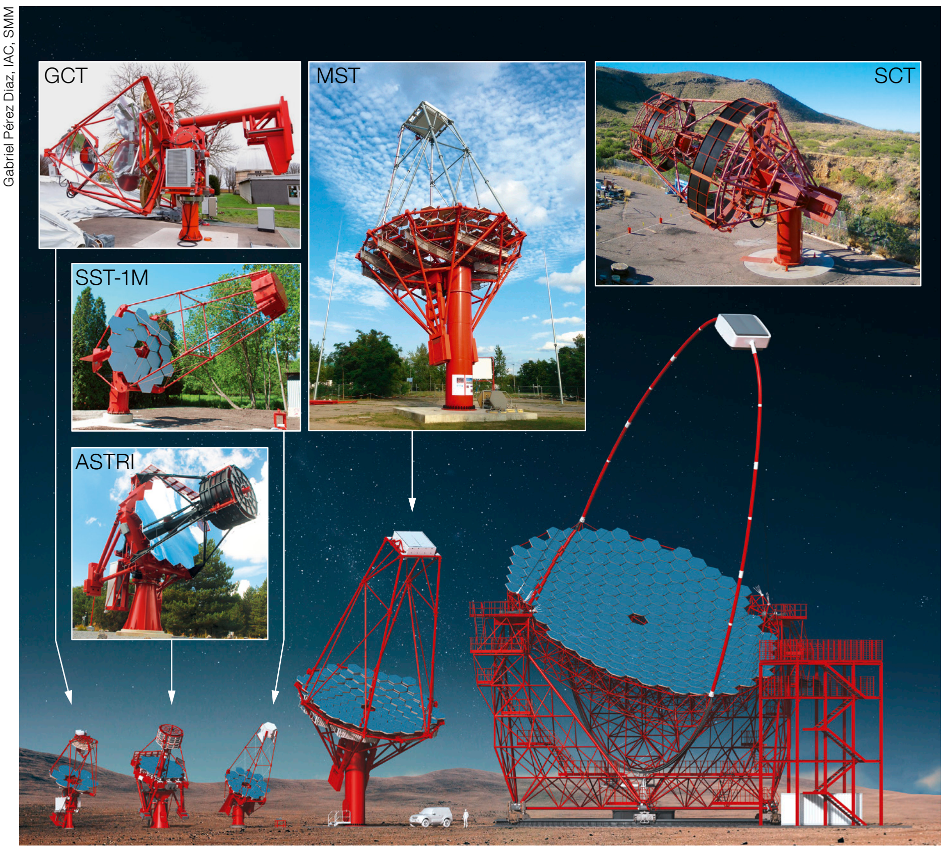
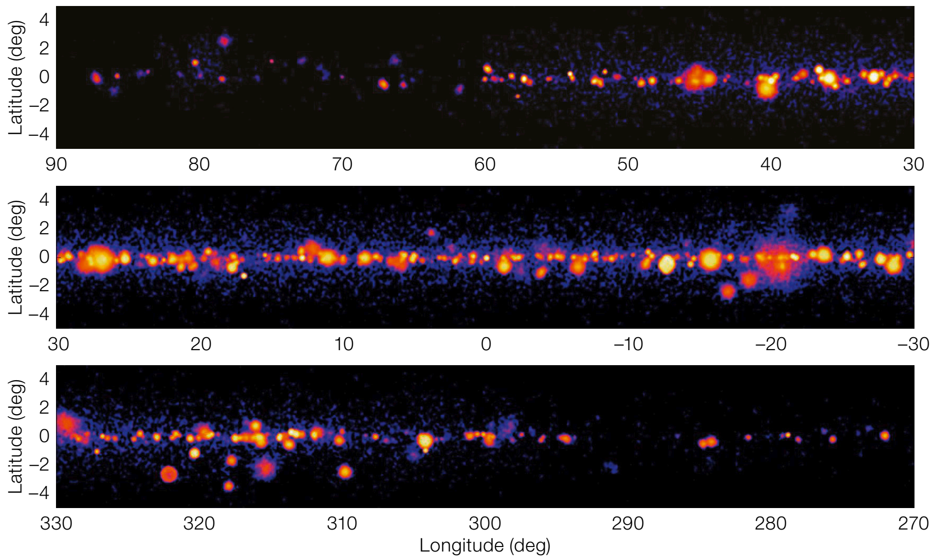


Figure 5. Main image: CAD models of the different CTA telescopes, shown to scale. The Small-Sized Telescopes (SST, from left: GCT, ASTRI, SST-1M) have a mirror diameter of about 4 metres, the Medium-Sized Telescope (MST, middle) has a 12-metre mirror, and the Large-Size Telescope (LST) a 23-metre mirror. Insets: Prototypes of CTA telescopes under test: GCT (at Meudon), ASTRI (on Sicily), SST-1M (at Warsaw), MST (at Berlin), and SCT (in Arizona). Construction of an LST prototype has started on La Palma (not shown).

for detailed simulations of the air showers and the response of the telescopes (Bernlöhr et al., 2013).

The parameters of the telescopes are summarised in Table 1. The different telescopes (Figure 5) have rather different design drivers. For example, the main drivers for the LSTs are the huge light-collecting power and rapid repositioning requirements (needed in particular for follow-up of γ-ray bursts), and for the SSTs the large number of elements implies tight constraints on unit cost and maintenance effort. Three different SST designs are being prototyped, the Gamma-ray

Figure 6. Simulation of the Milky Way seen with CTA in very-high-energy γ-rays.



Cherenkov Telescope (GCT) and the Astrofisica con Specchi a Tecnologia Replicante Italiana (ASTRI) dual-mirror telescopes and the SST-1M single-mirror variant. The dual-mirror telescopes use Schwarzschild-Couder (SC) optics, realised for the first time in CTA's Cherenkov telescopes. Also, a dual-mirror version of the MST is being considered (SCT); compared to the classical single-mirror Cherenkov telescopes; the novel dual-mirror telescopes offer improved imaging quality and allow a smaller plate scale and rather compact cameras. The LST and MST with their large (3-metre) cameras use photomultipliers with very high quantum efficiency to detect the Cherenkov light, whereas the smaller sensor areas of the SSTs and the SCT are covered with silicon sensors.

The CTA Observatory

The CTA facility will be open to a wide community of scientific users: from astronomy and astrophysics, to astroparticle physics, particle physics, cosmology and plasma physics. CTA observation time and data products will be provided to users through several different modes:
- The Guest Observer Programme is a proposal-based system that will give users access to time for observations requiring anywhere between a few hours and hundreds of hours.
- The Key Science Projects (KSPs) defined by the CTA Consortium are large programmes that ensure that the key science issues are addressed in a coherent fashion, generating legacy data products. KSPs require anything between 100 and 1000 hours of observation time.
- The Director's Discretionary Time will represent a small fraction of observation time that will be used for, for example, unanticipated targets of opportunity or outstanding proposals from non-member countries.
- Archive Access to CTA data will be made available worldwide after a proprietary period of about one year.

Observations will take place in service mode; the user may request specific telescope configurations, and specify trigger conditions, time constraints arising from coordinated observations with other observatories, etc. Users will receive processed and calibrated data in the form of photon-candidate event lists similar to the products of other photon-counting instruments, provided in the Flexible Image Transport System (FITS) format, together with relevant instrument response functions and auxiliary data, as well as science analysis tools.

Science data, calibration data and auxiliary data will be permanently stored in the CTA data archive and made available to archive users after the proprietary period. The data archive will remain available beyond the operational period of the CTA Observatory. High-level data, such as sky maps, light curves, and source catalogues will be made available in a Virtual Observatory (VO) compliant format. Alerts from CTA on noteworthy astronomical events (for example the detection of transients) will be sent to the wider community in the VO Event format.

The CTA Key Science Projects

The detailed volume *Science with the Cherenkov Telescope Array* is about to be published. Proposed CTA KSPs include: (i) the Dark Matter Programme; (ii) the Galactic Centre Survey; (iii) the Galactic Plane Survey; (iv) the Large Magellanic Cloud Survey; (v) the Extragalactic Survey; (vi) Transients; (vii) Cosmic-ray PeVatrons; (viii) Star-forming Systems; (ix) Active Galactic Nuclei; (x) Clusters of Galaxies; and (xi) Beyond gamma-rays. In the following, only the survey KSPs are briefly introduced; these will form a basis for subsequent guest observer proposals.

The combination of CTA's wide field of view (FoV) and its unprecedented sensitivity ensures that CTA can deliver surveys 1–2 orders of magnitude deeper than existing surveys very early in the life of the CTA Observatory. CTA surveys will open up discovery space in an unbiased way and generate legacy datasets of long-lasting value. The following surveys form part of the KSPs:
- The Extragalactic Survey — covering one quarter of the sky to a depth of ~ 6 mCrab. No extragalactic survey has ever been performed using IACTs. A 1000-hour CTA survey of such a region will reach the same sensitivity as the decade-long HESS programme of inner-Galaxy observations, and cover a solid angle ~ 40 times larger, providing a snapshot of activity in an unbiased sample of galaxies.
- The Galactic Plane Survey (GPS) — consisting of a deep survey (~ 2 mCrab) of the inner Galaxy and the Cygnus region, coupled with a somewhat shallower survey (~ 4 mCrab) of the entire Galactic Plane (see Figure 6). For the typical luminosity of known Milky Way TeV sources of $10^{33–34}$ erg s^{-1}, the CTA GPS will provide a distance reach

of ~ 20 kpc, detecting essentially the entire population of such objects in the Galaxy and providing a large sample of objects one order of magnitude fainter. The excellent angular resolution of CTA is critical here if it is to avoid being limited by source confusion rather than flux.
– The Galactic Centre Survey — consisting of a > 500 hours deep exposure of a ± 1 degree window around Sgr A*, covering the Galactic Centre source, the centre of the Dark Matter halo, multiple supernova remnants and pulsar wind nebulae, central radio lobes and arc features. An additional 300 hours extended survey covers a 10 by 10 degree region around Sgr A*, including the edge of the Galactic Bulge, the base of the Fermi Bubbles, the radio spurs and the Kepler supernova remnant.
– The Large Magellanic Cloud (LMC) Survey — providing a face-on view of an entire star-forming galaxy, resolving regions down to 20 pc in size with sensitivity down to luminosities of ~ 10^{34} erg s^{-1}. CTA aims to map the diffuse LMC emission as well as individual objects, providing information on relativistic particle transport.

These surveys will establish the populations of VHE emitters in Galactic and extragalactic space, providing samples of objects large enough to understand source evolution and/or duty cycle. Data products from the survey KSPs include catalogues and flux maps which will serve as valuable long-term resources for a wide community. The value of these surveys is not only that they provide the basis for a population synthesis of cosmic particle accelerators, but also that they enable discovery of key objects — the equivalents of the Hulse-Taylor pulsar or the Double Pulsar found in radio pulsar surveys.

Construction of the CTA

The Design Phase of CTA has been concluded; the project is currently near the end of the Pre-Construction Phase in which instrument designs were evolved to production readiness and were reviewed in the Science Performance and Requirements Review, the Preliminary Design Review and the final Critical Design Review — all performed by CTA's Science and Technical Advisory Committee.

The forthcoming Pre-Production Phase covers the deployment of approximately 10 % of the final number of telescopes with the aim of verifying and optimising production schemes, as well as exercising and optimising deployment, testing software, etc. Based on the Pre-Production Readiness/Deployment Reviews, Pre-Production telescopes will be installed on the sites; after retrofitting to final production status where relevant, they are planned to be used in the final CTA arrays.

Once Pre-Production is successfully established for a given telescope type, this element moves to the Production Phase. To first approximation, telescopes are not dependent on each other for operation and the cumulative completion of the full scope of the arrays may progress gradually. Science operation will start with partial arrays, before deployment of the full arrays is completed. Telescopes are successively handed over from the construction project to operations. Prior to user science operation, the performance of the (initially partial) arrays will be verified and documented. It is anticipated that construction activities will start in 2018, with the first data from partial arrays becoming available in 2021.

In summary, CTA will provide a next-generation VHE γ-ray observatory with unprecedented capability. CTA perspectives in relativistic astrophysics include the in-depth understanding of known VHE γ-ray emitters and their mechanisms, detection of new object classes and discovery of new phenomena. As with many facilities breaking new ground, the most important discoveries may not be the ones discussed in today's science case documents.

References

Acharya, B. S. et al. 2013, Astroparticle Physics, 43, 3
Bernlöhr, K. et al. 2013, Astroparticle Physics, 43, 171
Hillas, A. M. 2013, Astroparticle Physics, 43, 19

Links

[1] CTA Observatory: www.cta-observatory.org
[2] For an overview of CTA science, see articles in the Special CTA edition of Astroparticle Physics, 43, 1-356, 2013
[3] Contributions of CTA to the 6th International Symposium on High-Energy Gamma-Ray Astronomy (Gamma 2016), arXiv:1610.05151

The panorama from the planned site of the Cherenkov Telescope Array looking towards the Very Large Telescope on Cerro Paranal.