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CTA: The Cherenkov Telescope Array

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Summary. — Ground-based gamma-ray astronomy has had a major breakthrough with the impressive results obtained using systems of imaging atmospheric Cherenkov telescopes. Ground-based gamma-ray astronomy has a huge potential in astrophysics, particle physics and cosmology. CTA is an international initiative to build the next generation instrument, with a factor of 5–10 improvement in sensitivity in the 100 GeV to 10 TeV range and the extension to energies well below 100 GeV and above 100 TeV. CTA will consist of two arrays (one in the Northern hemisphere and one in the Southern hemisphere) for full sky coverage and will be operated as an open observatory. This paper briefly reports on the status and presents the major design concepts of CTA.

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1. – Introduction

In the field of very-high-energy gamma-ray astronomy (VHE, energies > 100 GeV(1)), the instruments H.E.S.S. [1], MAGIC [2] and VERITAS [3] have been driving the development in recent years. The spectacular astrophysics results from the current Cherenkov instruments have generated considerable interest in both the astrophysics and particle physics communities and have created the desire for a next-generation, more sensitive and more flexible facility, able to serve a larger community of users. The proposed CTA [4] is a large array of Cherenkov telescopes of different sizes, based on proven technology and deployed on an unprecedented scale (fig. 1). It will allow significant extension of our current knowledge in high-energy astrophysics. CTA is a new facility, with capabilities well beyond those of conceivable upgrades of existing instruments such as H.E.S.S., MAGIC or VERITAS. The CTA project unites the main research groups in this field in a common strategy, resulting in an unprecedented convergence of efforts, human resources,

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(1) 1 GeV = 10^9 eV; 1 TeV = 10^{12} eV; 1 PeV = 10^{15} eV.

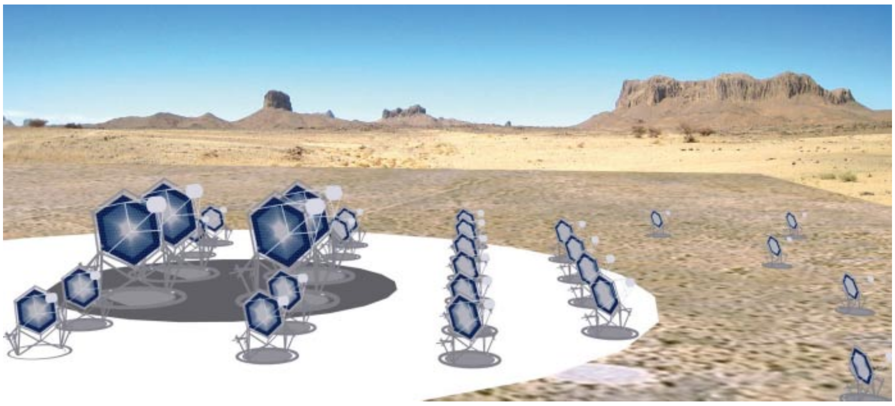

Fig. 1. – Conceptual layout of a possible Cherenkov Telescope Array (not to scale).

and know-how. Interest in and support for the project is coming from scientists around the world, all of whom wish to use such a facility for their research and are willing to contribute to its design and construction. CTA will offer worldwide unique opportunities to users with varied scientific interests. In particular, the number of young scientists working in the still evolving field of gamma-ray astronomy is growing at a steady rate, drawing from other fields such as nuclear and particle physics. In addition, there is increased interest by other parts of the astrophysical community, ranging from radio to X-ray and satellite-based gamma-ray astronomers. CTA will, for the first time in this field, provide open access via targeted observation proposals 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. Details on the science cases and on technical implementations of CTA can be found in [5]. This article gives a brief overview and updates on the status of the project.

2. – Status of the field

Radiation at gamma-ray energies differs fundamentally from that detected at lower energies and hence longer wavelengths: GeV to TeV gamma rays cannot conceivably be generated by thermal emission from hot celestial objects. The energy of thermal radiation reflects the temperature of the emitting body, and apart from the Big Bang there is and has been nothing hot enough to emit such gamma rays in the known Universe. Instead, we find that high-energy gamma rays probe a non-thermal Universe, where other mechanisms allow the concentration of large amounts of energy onto a single quantum of radiation. In a bottom-up fashion, gamma rays can be generated when highly relativistic particles – accelerated for example in the shock waves of stellar explosions – collide with ambient gas, or interact with photons and magnetic fields. The flux and energy spectrum of the gamma rays reflects the flux and spectrum of the high-energy particles. They can therefore be used to trace these cosmic rays and electrons in distant regions of our own galaxy or even in other galaxies. High-energy gamma rays can also be produced in a top-down fashion by decays of heavy particles such as hypothetical dark matter particles or cosmic strings, both of which might be relics of the Big Bang. Gamma rays therefore provide a window on the discovery of the nature and constituents of dark matter.

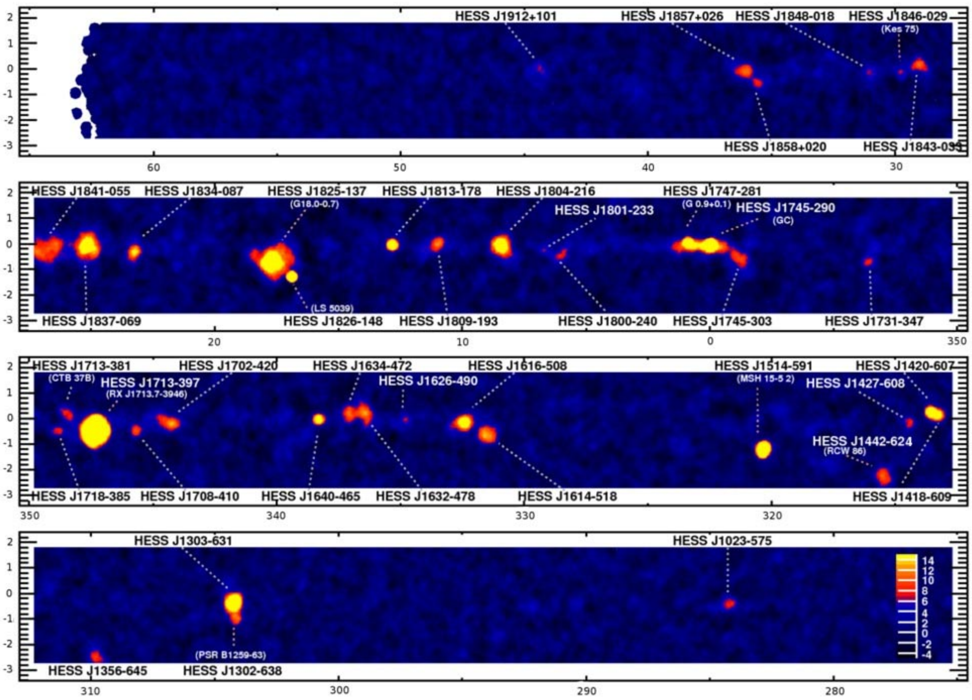

Fig. 2. – The Milky Way viewed in VHE gamma rays, in four bands of galactic longitude [8].

In the recent years, more than 150 galactic and extragalactic sources have been detected in VHE gamma rays. The H.E.S.S. galactic plane survey (see fig. 2) provided the first deep survey in VHE gamma rays of the Milky Way. Many pulsar wind nebulae have been found making them the most common objects to emit gamma rays in our galaxy. Deep observations of selected objects enabled detailed images of extended sources like the supernova remnant RX J1713.7-3946 or W51C. Several X-ray ray binaries have been identified to emit gamma rays. Another highlight of the galactic observations was a discovery of the Crab pulsar to emit gamma rays with energies up to at least 400 GeV. The sources of VHE gamma rays in the extragalactic sky are mostly blazars: the active galactic nuclei harboring super-massive black holes in their centers. In blazars, the ultra-relativistic jets point towards us boosting the VHE emission, which eases their detection. The furthest blazar to emit VHE gamma rays is 3C 279 at $z = 0.536$. Several radio galaxies have been observed to emit gamma rays: M 87, Cen A and NGC 1275. Very deep observations (more than 150 hrs per source) were done to also detect the starburst galaxies M 82 and NGC 253. These detections are important because these sources do not have strong jets. With the data available, not only source physics is being studied. The observed gamma rays also allow for studying fundamental physics such as the Lorentz Invariance Violation, search for dark matter as well as probing star and galaxy formation and cosmological models. The discovered source classes, their morphologies, observed time variability and spectral energy distributions cannot be more than the tip of the iceberg of a richer panorama that is yet to be discovered. For recent review of the status of the gamma-ray astronomy see, *e.g.*, [6, 7].

2·1. *Detection technique*. – The recent breakthroughs in VHE gamma-ray astronomy were achieved with ground-based Cherenkov telescopes. When a VHE gamma ray enters the atmosphere, it interacts with atmospheric nuclei and generates a shower of secondary electrons, positrons and photons. Moving through the atmosphere at speeds higher than the speed of light in air, these electrons and positrons emit a beam of bluish light, the Cherenkov light. For near vertical showers this Cherenkov light illuminates a circle with a diameter of about 250 m on the ground. For large zenith angles the area can increase considerably. This light can be captured with optical elements and be used to image the shower, which vaguely resembles a shooting star. Reconstructing the shower axis in space and tracing it back onto the sky allows the celestial origin of the gamma ray to be determined. Measuring many gamma rays enables an image of the gamma-ray sky, such as that shown in fig. 2, to be created. Large optical reflectors with areas in the $100\,\mathrm{m}^2$ range and beyond are required to collect enough light, and the instruments can only be operated in dark nights at clear sites. With Cherenkov telescopes, the effective area of the detector is about the size of the Cherenkov pool at ground. As this is a circle with 250 m diameter this is about $10^5\times$ larger than the size that can be achieved with satellite-based detectors. Therefore much lower fluxes at higher energies can be investigated with Cherenkov Telescopes, enabling the study of short time scale variability.

2·2. *Existing facilities*. – The Imaging Atmospheric Cherenkov Technique was pioneered by the Whipple Collaboration in the United States. After more than 20 years of development, the Crab Nebula, the first source of VHE gamma rays, was discovered in 1989. The Crab Nebula is among the strongest sources of very high energy gamma rays, and is often used as a "standard candle". Modern instruments, using multiple telescopes to track the cascades from different perspectives and employing fine-grained photon detectors for improved imaging, can detect sources down to 1% of the flux of the Crab Nebula, see, *e.g.*, [6].

At the moment, three big installation are in operation: The H.E.S.S. Collaboration operates four 12 m diameter Cherenkov telescopes in Namibia, near the Gamsberg mountain since 2003. The MAGIC Collaboration operates two 17 m diameter Cherenkov telescopes on La Palma, Canary Islands. The mono observations started in 2004 while the second telescope and the stereo observations came into operation in October 2009. The VERITAS Collaboration operates four 12 m diameter Cherenkov telescopes in southern Arizona, USA since 2007. Both, MAGIC and VERITAS telescopes operate in the Northern hemisphere, whereas the H.E.S.S. array is in the Southern hemisphere. Given the relatively small field of view of the instruments (3.5 to 5°), the instruments are mainly complementary to each other while, at the same time, it is possible to cross-calibrate them by observing steady gamma-ray sources visible from both hemispheres [9].

3. – Physics drivers

The aims of the CTA (as well as of the current generation instruments) can be roughly grouped into three main themes, serving as key science drivers:

Understanding the origin of cosmic rays and their role in the Universe: This comprises the study of the physics of galactic particle accelerators, such as pulsars and pulsar wind nebulae, supernova remnants, and gamma-ray binaries. It deals with the impact of the accelerated particles on their environment (via the emission from particle interactions with the interstellar medium and radiation fields), and the cumulative effects seen at various scales, from massive star forming regions to starburst galaxies.

Understanding the nature and variety of particle acceleration around black holes: This concerns particle acceleration near super-massive and stellar-sized black holes. Objects of interest include microquasars at the galactic scale, and 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. Extragalactic background light (EBL), galaxy clusters and gamma-ray burst (GRB) studies are also connected to this topic.

Searching for the ultimate nature of matter and physics beyond the Standard Model: This covers what can be called "new physics", with searches for dark matter through possible annihilation signatures, tests of Lorentz invariance, and any other observational signatures that challenge our current understanding of fundamental physics.

CTA will be able to generate significant advances in all these areas.

4. – Realizing CTA

4·1. *General concept.* – The key elements of the CTA array are:

- Two observatories, one in the Southern hemisphere and one in the Northern hemisphere to cover the whole sky.
- Much (a factor of 5–10) improved sensitivity compared to the current instruments. The goal is to achieve a mCrab integral sensitivity (*i.e.* to detect a clear signal from a source with a flux of 0.1% of the Crab Nebula flux in 50 h of observations) or better.
- Wide energy range. The Cherenkov technique allows one to detect gamma rays with energies from tens of GeV (using few large telescopes to collect as much light from a single shower as possible) up to hundreds of TeV (using many small telescopes to cover as much area as possible).
- Superb angular resolution. To study morphology of galactic sources an improved angular resolution down to arcmin scale is required and can be achieved by using fine pixelized cameras.
- Temporal resolution. With its large detection area, CTA will resolve flaring and time-variable emission on sub-minute time scales, which are currently not accessible.
- Survey capability. One of the main goals of CTA will be to produce a detailed GeV-TeV map of our galaxy. This is achievable by constructing a flexible in configuration array of telescopes with 6–8° field-of-view cameras.

4·2. *Monte Carlo simulations and layout studies.* – A particular size of Cherenkov telescope is only optimal for covering about 1.5 to 2 decades in energy. Three sizes of telescope are therefore needed to cover the large energy range CTA proposes to study (from a few tens of GeV to above 100 TeV). The current baseline design consists of three telescope types: SST: Small size telescopes of 5–8 m diameter, both single-mirror and dual-mirror designs are considered; MST: Medium size telescopes of 10–12 m diameter, both single-mirror and dual-mirror designs are considered; and LST: Large size single-mirror telescopes of 23 m diameter.

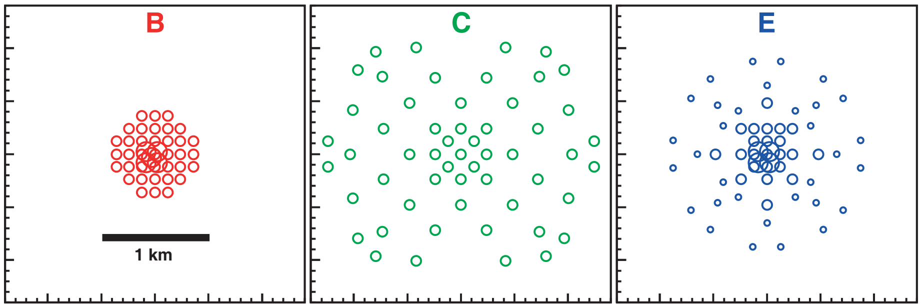

Fig. 3. – Three example candidate arrays (B, C and E) are among the studied configurations that would have an approximately similar construction cost.

Several different telescope configurations have been investigated in simulation studies for CTA so far. The first simulations were used to cross-check the different simulation packages and to begin the investigation of the dependence of performance on telescope and array parameters. The evaluation of the performance of these candidate arrays is a first step towards the optimisation of the CTA design. Figure 3 shows some of the telescope layouts used. All systems assume conventional technology for mirrors, PMTs and read-out electronics. Standard analysis techniques are used in general, with the results from more sophisticated methods shown for comparison in specific cases. Preliminary results as illustrated for the integral sensitivity and angular resolution in fig. 4 show that the ambitious goals of CTA are within the reach.

4˙3. *CTA telescope technology*. – The CTA telescope technology is mainly based on known concepts and makes a heavy use of the experience in the field of Cherenkov telescopes. Several designs of different telescope types (SST, MST and LST, see above) are being developed with an optimal cost/performance ratio.

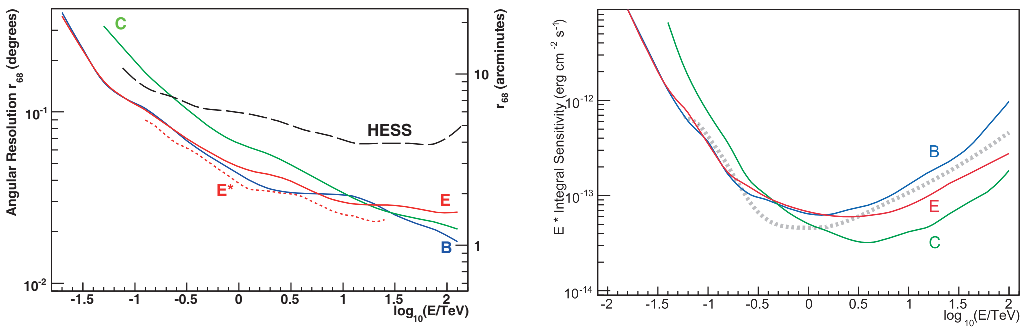

Fig. 4. – Left: Angular resolution (68% containment radius of the gamma-ray PSF) *versus* energy for the candidate configurations B, C and E. The resolution for a more sophisticated shower axis reconstruction method for configuration E is shown for comparison (dashed red line—E*). Right: Integral sensitivity (multiplied by E) for the candidate configurations B, C and E, for point sources observed for 50 hours at a zenith angle of 20°. The goal curve for CTA (dashed line) is shown for comparison.

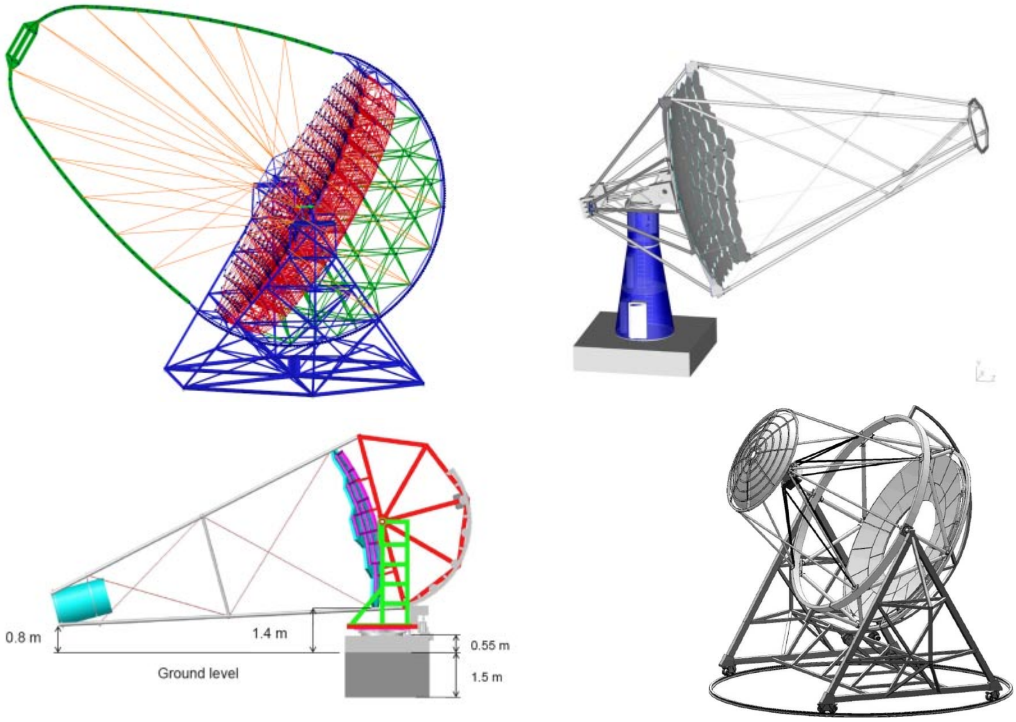

Fig. 5. – Top left: concept of a 23 m diameter LST with parabolic dish and $f/d = 1.2$. Top right: concept of a 12 m diameter MST with a Davies-Cotton dish and $f/d = 1.4$. Bottom left: concept of a 6 m diameter SST with a Davies-Cotton dish and $f/d = 1.4$. Bottom right: concept of a dual mirror Schwarzschild-Couder MST telescope.

Concepts of different telescope structures are illustrated in fig. 5. Schwarzschild-Couder telescopes with their dual optic are more difficult to construct because of the precision of the optical surface needed but if realized they would offer a possibility for a smaller (more compact and less expensive) cameras combined with a large field of view. The other designs assume a single reflector telescopes allowing for adequate fields of view for the costs of larger cameras. Imaging is improved by choosing relatively large f/d values, in the range of 1.2 to 1.5. A second variable is the dish shape: a Davies-Cotton layout provides good imaging over wide fields, but introduce a time dispersion. For small dish diameters this dispersion is smaller than the intrinsic width of the photon distribution, and therefore insignificant. For large dish diameters, the difference in photon path length from different parts of the reflector becomes larger than the intrinsic spread of photon arrival times, broadening the light pulse.

As the photosensor photomultiplier tubes (PMTs) are planned to be used. PMTs are very linear devices with a large (4 orders of magnitude) dynamic range and they allow the detection of single Cherenkov photons. Moreover PMTs are fast (photoelectrons signal widths below 3 ns duration), which is important to suppress background in the images. The camera of a CTA telescope will consist of 500 to 2000 PMTs depending on the telescope type and has strict limits on the weight and needed cooling power. To read out the signals from the cameras several concepts exist. The readout system must ensure a large bandwidth and low noise in order not to degrade the signal quality. It must also have small dead time and a sufficient buffer to allow for a trigger decision. The leading concepts use analogue sampling memory based recording systems. An alternative design using a 250 MSample/s system is based on a commercial low-cost FADC.

Hardware prototyping is under way for most of the parts to confirm simulated or expected results. The prototyping is also needed to confirm the costs estimates for the array construction and maintenance.

4˙4. *CTA as an open observatory.* – Unlike current ground-based gamma-ray instruments, CTA will be an open observatory, with a Science Data Centre (SDC) which provides pre-processed data to the user, as well as the tools necessary for the most common analyses. The software tools will provide an easy-to-use and well-defined access to data from this unique observatory. CTA data will be accessible through the Virtual Observatory, with varying interfaces matched to different levels of expertise. The required toolkit is being developed by partners with experience in SDC management from, for example, the INTEGRAL space mission.

5. – Conclusions

The CTA observatory is the logical next step in the exploration of the high-energy Universe, and will promote VHE observations as a public tool for modern astronomy. CTA will explore the VHE domain from several tens of GeV up to more than 100 TeV with unprecedented sensitivity and angular resolution, enabling a comprehensive understanding of cosmic particle acceleration physics at various scales, distances and time scales. Major advances are expected in understanding the origin of galactic cosmic rays, their propagation within galaxies, and their impact on their environment. Particle acceleration in the vicinity of black holes will be explored in a large variety of sources, and interactions and feedback effects of the particles on their surroundings will be explored. CTA will also probe physics beyond the established horizon, holding promise for a better understanding of the ultimate laws that govern the Universe. The CTA project started a preparatory phase in 2011, and array deployment could begin as early as 2016, with a full observatory operational before the end of this decade. Early science may be optimistically expected from 2017–2018 on.

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REFERENCES

[1] `http://www.mpi-hd.mpg.de/hfm/HESS`.
[2] `http://magic.mppmu.mpg.de`.
[3] `http://veritas.sao.arizona.edu`.
[4] `http://www.cta-observatory.org`.
[5] Actis M. *et al.* (CTA Consortium), *Exp Astron*, **32** (2011) 193.
[6] Hinton J. A. and Hofmann W., *Annu. Rev. Astron. Astrophys.*, **47** (2009) 523.
[7] Funk S., *32nd ICRC, China, 2011* (2012) arXiv:1204.4529.
[8] See, *e.g.*, Aharonian F. A., *Astrophys. J.*, **636** (2006) 777 (and subsequent presentations in conferences).
[9] See, *e.g.*, Meyer M. *et al.*, *Astron. Astrophys.*, **523** (2010) A2.