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The (future) Cherenkov Telescope Array CTA

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Summary. — The international CTA consortium has recently entered the preparatory phase towards the construction of the next-generation Cherenkov Telescope Array CTA. This experiment will be a successor to and will benefit from the return of experience from the three major current-generation arrays H.E.S.S., MAGIC and VERITAS. It aims to significantly improve upon the sensitivity as well as the energy range of its highly successful predecessors. Construction is planned to begin by 2014, and when finished, CTA will be able to explore the highest-energy gamma-ray sky in unprecedented detail. The current status of the CTA project is presented, together with its expected performance based on Monte Carlo studies.

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1. – Introduction: Cherenkov telescopes

1·1. *Physical motivation.* – The observation of photons of different wavelengths has for a long time been the most important tool in astronomy. Initially using only visible light, this effort now spans the whole wavelength band from radio waves to gamma rays. At the highest energies (above $\sim 100\,\text{GeV}$), the Imaging Atmospheric Cherenkov telescope is currently the most successful technology for the detection and observation of both galactic and extragalactic TeV gamma-ray sources. Among others, possible extragalactic targets of interest are the nuclei of active galaxies (AGNs), including blazars and radio galaxies, and gamma-ray bursts (GRBs). Galactic source candidates in this energy range are pulsars and their wind nebulae (PWNs), supernova remnants, binary systems and microquasars. As these possible targets are not uniformly distributed over the sky, the scientific impact of a Cherenkov observatory will depend on its location: As the galactic plane is mainly confined to the Southern sky, observation of galactic sources are best carried out from Southern locations, while Northern sites are more suited to extragalactic observations.

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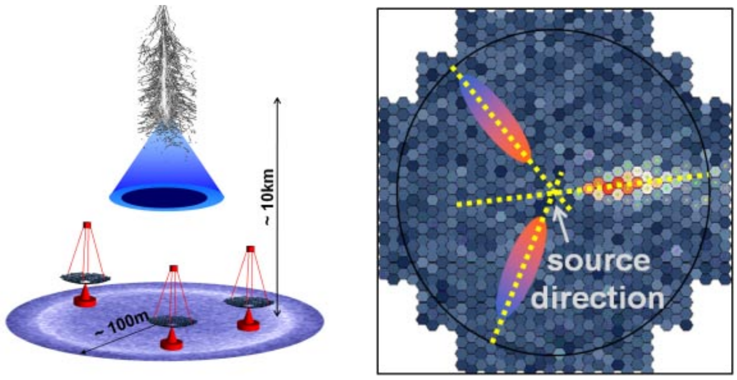

Fig. 1. – Left: Sketch of the detection technique. Not to scale. Right: Shower image in one camera, overlayed with reconstructed shower images from other cameras.

Cherenkov telescopes are also important contributors to multi-wavelength and multi-messenger campaigns, where they observe jointly with instruments operating in other wavelength domains (such as optical or X-ray) or observation channels (such as neutrinos or gravitational waves).

In addition to those astrophysical sources, Cherenkov telescopes also contribute to the search for new physics, such as dark matter or quantum gravity.

1˙2. *Detection technique*. – To detect the decreasing fluxes of gamma rays at multi-TeV energies, very large detection volumes are necessary. In gamma Cherenkov telescopes, this is achieved by using the Earth's atmosphere as detector (as sketched in fig. 1): The primary gamma rays interacting in the upper atmosphere are converted to electromagnetic showers, whose charged components emit Cherenkov light in a narrow cone along the shower's direction (opening angle about 1 degree). This light can be detected several kilometres below by an array of optical telescopes equipped with very sensitive high-speed cameras. From the light distribution in these cameras, the original shower geometry can be reconstructed, giving the direction, energy and type of the primary particle. In systems with several telescopes, the individual camera images can be combined to provide a stereoscopic view of the shower, significantly improving the system's resolution and background suppression capabilities (fig. 1, right). In order to detect the faint Cherenkov light of the atmospheric showers, the atmospherical quality at the telescope site is subject to stringent requirements, in particular high altitude, clean and dry air, and the absence of light pollution. Consequently, all current systems are generally located in remote locations such as deserts or mountain tops.

1˙3. *Current generation of Cherenkov telescopes*. – The gamma Cherenkov technology has steadily evolved over the last few decades, with several subsequent generations of instruments, each improving in sensitivity upon its precedessors. The current generation is represented by three systems in different locations on the Earth, the H.E.S.S. array in Namibia, the MAGIC telescopes on the Canary Islands and the VERITAS system in Arizona.

– The High Energy Sterescopic System H.E.S.S.: Phase 1 of the H.E.S.S. system comprises four telescopes, of 107 m^2 surface area each, that are operated at an altitude of 1800 m in the Khomas highland in Namibia [1].

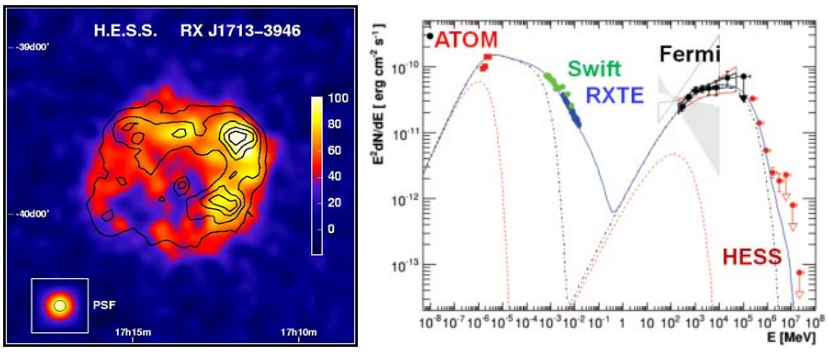

Fig. 2. – Example results for current-generation systems. Left: Extended source RX-J1713 as measured by H.E.S.S., showing clear shell-like sub-structures. Right: Multiwavelength spectrum obtained by H.E.S.S. together with several ground- and space-based telescopes, from [4].

– MAGIC I+II: Located on the top of the Canary Island of La Palma, at an altitude of 2225 metres. In contrast to the four medium-sized telescopes used in the H.E.S.S. array, the MAGIC project used in its first phase of operation a single, large telescope ($234\,\mathrm{m}^2$) to decrease the energy threshold at the expense of sensitivity at higher energies. This telescope has recently been joined by a second large telescope, in the MAGIC-II phase [2].

– VERITAS: The second system on the Northern hemisphere is located in Arizona, USA, at the Fred Lawrence Whipple Observatory. It consists of four $106\,\mathrm{m}^2$ telescopes in an array, similar to the H.E.S.S. system [3].

– System upgrades: To increase their performance, and to cover the time until the arrival of a next-generation system, both the H.E.S.S. and the MAGIC telescope systems are currently undergoing technical upgrades: a second telescope was added to the MAGIC site in 2009 to allow stereoscopic observations, and at the H.E.S.S. site a single large telescope (23 m diameter) is currently under construction, to significantly improve the system's sensitivity at lower energies.

1˙4. *Example results*. – Due to their relatively good angular resolution and sensitivity, the current telescope systems have, for the first time, been able to provide spatially resolved images of a variety of extended objects, such as shell-type supernova remnants, and have made it possible to study their emission morphology (fig. 2, left). On the other hand, the unprecedented flux sensitivity offers the possibility to follow the temporal development of variable emitters, such as either periodic (like pulsars) or flaring sources (such as AGNs). In addition to dedicated observations of individual sources, sky surveys have also been performed. These have lead to the detection of many sources with or without prior-known counterparts at other wavelength bands. Cherenkov telescopes have played an important role in recent multi-wavelength campaigns, together with satellites and ground-based telescopes operating in other wavelength bands (see, for example, fig. 2, right, for a spectrum measured in a multi-wavelength campaign where H.E.S.S. contributed in the high-energy cut-off region important for model discrimination).

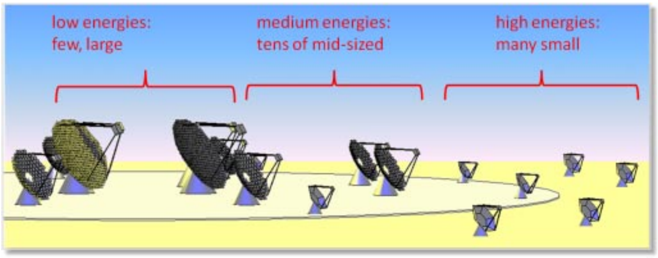

Fig. 3. – Artist's sketch of the different telescope types.

2. – The next-generation array CTA

2·1. *Motivation.* – While the current-generation Cherenkov telescopes have provided many discoveries and important scientific results, it has become clear that there is a range of phenomena and source types which are just out of reach of their sensitivity, or whose detailed analysis would require significantly better statistics than currently available. This required improvement in statistical power could be achieved by improving the differential flux sensitivity by about an order of magnitude. Possible new sources within reach of such an improved system could include among others: colliding supernova winds (galactic), starburst galaxies, galaxy clusters and gamma-ray bursts (all extra-galactic). In addition, improved limits on dark matter models and quantum gravity effects—or their discovery—are also be expected.

2·2. *The array.* – For this purpose, the CTA consortium is working on the design of a next-generation telescope system, the Cherenkov Telescope Array (CTA). It will consist of a large number (up to 100) of telescopes of three different sizes, at two sites (one Northern, one Southern). To improve the sensitivity at the lowest energies (below $\sim 100\,\text{GeV}$, moving the threshold down to about $20\,\text{GeV}$), several large-size telescopes (LST) with diameters around 24 metres will be used to collect the faint light emitted by those showers. At the highest energies (several tens to hundreds of TeV), the limiting factor is the dwindling flux of particles; to compensate for that, CTA will use a large number of sparsely distributed small-size telescopes (SST), offering a total detection area greater than a few km^2 at a reasonable cost. The workhorse of the system will be an array of medium-sized telescopes (MST), whose main goal is to improve the flux sensitivity in the mid-energy range (between $100\,\text{GeV}$ and $> 30\,\text{TeV}$) down to the milli-Crab level.

In accordance with the different physics goals for the Northern and Southern site, the two arrays will likely have a different combination of the three telescope sizes.

2·3. *The CTA consortium.* – The construction and operation of such a system of up to 100 telescope units will require substantial funding and manpower; in particular, it will not be possible without a major international collaboration. For that reason, the CTA consortium has been founded, which now comprises most of the members of the three current-generation collaborations (H.E.S.S., MAGIC and VERITAS), as well as several other groups from all around the world. The CTA project is supported by the European ESFRI([1]) roadmap [5] and has received funding both from national agencies and from

([1]) The *European Strategy Forum on Research Infrastructures*.

the European Union for the design study and preparatory phase. The CTA consortium reveived funding from ESFRI for the preparation of the construction within 3 years. In addition, it was cited as one of the top-priority near-term projects on the ASPERA([2]) 2008 roadmap [6], as well as being one of the two projects targeted by the 2009 ASPERA common call for cross-national funding.

The CTA design study was finished in 2010 [7]. Prototyping is planned for 2011 to 2013, Construction is expected to begin by 2014. Observation with the partial array will start soon after, while the full array is still under construction.

2˙4. *CTA as a gamma observatory.* – One particularity that will set CTA apart from its predecessors is the plan to operate it - at least partially - as an open observatory, where access to the data is not limited to members of the collaboration. Instead, it is envisaged that external groups can apply for observation time on the array. The different observation proposals will be evaluated by a peer-review process, and selected proposals granted observation time. The observation itself will be performed by experts from the CTA consortium, so that no technical knowledge of the system will be required for the submitters of the proposals. Likewise, it is forseen that a suite of analysis tools will be made available, to perform standard analyses on the data without deeper knowledge of the CTA software.

In addition to these on-demand observations, it is forseen to produce a set of *legacy data* in the form of sky scans (either in-depth scans of the galactic plane or a full-sky survey at lower exposure).

3. – Towards the array

The design goals for the CTA array are: an improvement of the sensitivity at TeV energies by about a factor 10 with respect to current experiments with, at the same time, a lowered energy threshold (a few tens of GeV) and a larger energy reach up to and beyond a few hundred TeV. Also, to allow for higher precision studies of extended sources, a better angular resolution (below 0.1 degrees above 100 GeV and 0.05 degrees above 1 TeV([3])) and a wide field of view are required. This will for the first time make it possible to resolve the inner structures of extended objects at a level of detail up to now visible only in other wavelength bands. With the large detection area, and thus high sensitivity, more precise studies of time-dependent sources, down to sub-minute time scales, will also be feasible.

3˙1. *Site search.* – Currently, several sites are under study for the Northern and Southern array, each of which fulfill the base requirements for the CTA observatory (altitude, clean and dry air, little light pollution). Apart from these physics requirements, there are other factors that are equally important for site selection. While for example remote sites typically offer the best observation conditions, they often have very limited available infrastructure (roads, power and data connections), making construction and operation of a large array difficult. The site should also be not prone to natural disasters (such as earthquakes or tornadoes). Current candidates include locations near the sites of the MAGIC and H.E.S.S. telescopes (the Canary Islands and the Khomas Highland

([2]) The *AStroParticle ERAnet*, a network of national government agencies responsible for coordinating and funding national research efforts in Astroparticle Physics.
([3]) 80% containment radius.

in Namibia, respectively), a site in the Baja California (Mexico) and in Arizona, as well as two sites in Argentina (El Leoncito and Salta). The task of choosing the final sites will be performed by the SITE work package in CTA.

3˙2. *Technology development*. – Being a successor to the currently operating telescope arrays, the development for CTA will profit strongly from existing designs and experience. In particular, working designs for the medium and large size telescopes exist already in the form of the H.E.S.S., VERITAS and MAGIC telescopes, as well as proven technology for the cameras and readout hardware. The construction of a large array of those telescopes, however, will not be possible without substantial modification and optimisation of those designs, as they were not conceived for mass-production or a high level of reliability (both of which are key requirements for CTA).

The task of technology development is currently shared by several workpackages in CTA, including one responsible for electronics, for the focal-plane instrumentation, for telescope mechanics, for data transfer, for mirrors, and others. Each of these groups is lead by experts from the current telescopes, and pursues several different technological options. For example, for the cameras there exist designs based on fully analogue schemes for triggering and readout, as well as designs using fully digital cameras.

For each of the most promising technological possibilities, prototypes will be developed. The final choice of the technology to use for CTA will be made on the basis of the performance of those prototypes, as well as on the cost and reliability of the different options. As several different telescope sizes will be used on two sites, it is possible that different technological options will be chosen for the various telescope types.

3˙3. *Data storage and transfer*. – To be able to handle the large amount of data that will be recorded by the system, substantial efforts are made for a GRID integration of CTA. This includes the development of software for easy access to the data from all participating institutions, as well as for data processing and analysis optimised for grid computing. For this purpose, the consortium has set up a CTA Virtual Observatory within the EU-funded EGEE project (Enabling Grids for E-Science). This is facilitated by the fact that several CTA member institutes are Tier 1 or 2 centres of the LHC computing grid and participate in the Cosmogrid.

While the main purpose of the GRID integration will be for storage, transfer and analysis of real data from the telescope system, the GRID is already being used for the extensive Monte Carlo simulations performed for the optimisation of the array's design.

3˙4. *Telescope structure*. – Each of the three telescope sizes envisaged for CTA will pose different kinds of challenges for its construction and operation:

For the large size telescope, the main challenge is the large size and weight of the structure. To guarantee good and stable optical properties of the telescope, it is important that the mirror does not deform under its own weight, or compensations must be done for any such deformation. This is also true for the mounting of the several-ton camera. For this reason, the use of strong, yet light, carbon-fibre based materials is evaluated. This will also help to keep the total weight low enough to allow sufficiently fast slewing of the telescopes. To compensate for any remaining deformation of the optical system, an active mirror control system could be employed, as is already the case for the MAGIC telescopes. The only design option being pursued for the LST is a single, facetted mirror, mounted on a rail support structure, such as used in H.E.S.S. and in MAGIC.

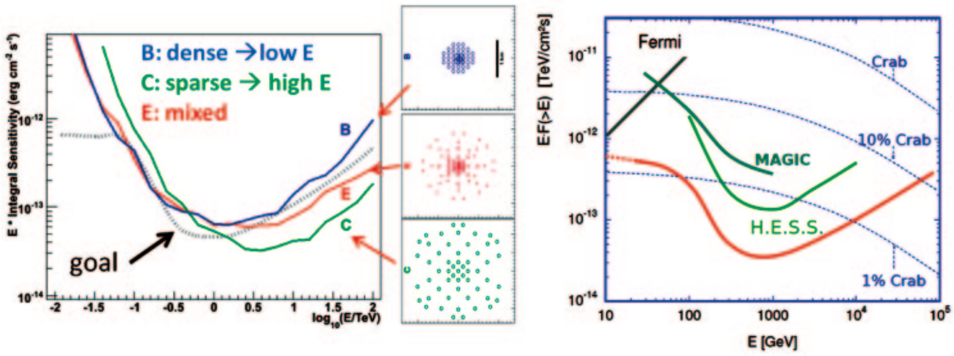

Fig. 4. – Left: Sensitivity of different sub-arrays from the simulation (B: dense, C: sparse, E: compromise), compared to the CTA design goal (dashed). Right: Expected sensitivity compared to current-generation Cherenkov telescopes and the Fermi satellite. Adapted from [7].

For the small-size telescopes, however, of which the largest number will be installed, ease of construction, a low unit cost and simplicity of operation are paramount. Currently, several possible designs for the SST are under evaluation. As a wide field of view is essential for the SSTs' operation (up to 10 degrees), a standard Davies-Cotton design [8] with a single mirror would require a relatively large, and rather expensive, camera. A possible alternative would be the use of a dual-mirror Schwarzschild-Couder design [9], which would allow for a much smaller camera, at the expense of a more complicated and costly mirror system. In this case, the camera would require smaller pixel sizes. Which of those options will be chosen for the final design will have to be determined based on feasibility and cost, and from experience with prototypes developed during the preparatory phase.

For the medium size telescopes, the technical challenges are less severe than for the LST. However, as this telescope type will serve as the workhorse of the CTA observatory, a significant number of those will have to be built, so that simplicity of design, robustness and reliability are crucial. Currently, as for the SST, several possible options are being studied, and prototypes planned. The preferred design uses of a single-mirror system, either rail- or tower-mounted.

In addition to these three telescope types, a $50\,\mathrm{m}^2$ dual-mirror Schwarzschild-Couder design is being investigated.

3˙5. *Monte-Carlo simulations*. – To evaluate the expected performance of the array, depending on the technological choices made and the different possible sites, extensive Monte Carlo studies are being undertaken. As the aim is to find the best possible combination of array geometry, telescope types and triggering and readout options for a given total cost, a large number of different options has to be simulated. For this purpose, a single "super-array" of several hundred telescopes in all sizes is simulated, and then split into appropriate sub-arrays of a comparable cost (around 80 million Euros for the Southern and 40 million for the Northern array). For these sub-arrays the system's effective area, as well as its sensitivity to different kinds of sources, can be calculated and compared (fig. 4, left). Most of this work is done with a standardised detector simulation [10] based on the CORSIKA shower propagation code [11]; for this purpose, a vast library containing on the order of 10^{11} showers has been produced. In addition to that, several dedicated simulations have been written for in-detail study of aspects such as alternative triggering and readout schemes.

As different arrays will not perform equally well at high and low energies, the final design choice will strongly depend on the physics goals pursued with CTA and will differ for the North and South array.

4. – Expected performance

Monte Carlo simulations have shown that with current designs the CTA science goals can be reached. Depending on the array configuration used, a milli-Crab sensitivity in the focus energy region seems realistic. A comparison (fig. 4, right) shows that CTA will indeed be much more sensitive (by a factor of about ten) than current experiments, over a wider energy range. The envisaged improvement of the angular resolution will also be achievable with the preferred candidate arrays. In addition, its sensitivity at low energies should provide a good overlap with satellite experiments (such as Fermi). As the reconstruction and analysis methods are still under development, those results are likely to improve in the future.

5. – Conclusions

Having finished the Design Study phase, the CTA consortium is now in the process of converging towards a final design for the telescope array. Technology development is well under way, so that array construction should proceed as planned. Monte Carlo studies confirm that the design sensitivity is reachable. With this expected sensitivity, TeV gamma astronomy will enter a new era, passing from the stage of first detections to precision measurements While its predecessors have been able to detect and measure of the order of a hundred objects, CTA is expected to study ten times as many at much higher precision, to literally "mass-produce physics discoveries". In this respect, it will be on par with the most successful last-generation experiments in other wavelength bands, such as Fermi for the soft gamma rays.

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We gratefully acknowledge support from the agencies and organisations listed in this page: `http://www.cta-observatory.org/?q=node/22`.

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