The Cherenkov Telescope Array (CTA) will be the next generation of ground based gamma-ray telescopes allowing us to study very high energy phenomena in the Universe. CTA aims to gain about a factor of ten in sensitivity compared to current experiments, extending the accessible gamma-ray energy range from a few tens of GeV to some hundreds of TeV. This increased gamma-ray source sensitivity, as well as the expected enhanced energy and spatial resolution, will allow exciting new insights in some key science topics. Additionally, CTA will provide a full sky-coverage by featuring the array located in two sites in the Northern and Southern hemispheres. This paper will describe the status of CTA and highlight some of CTA’s key science themes; namely the origin of relativistic cosmic particles, the study of cosmological effects on gamma-ray propagation and the search for annihilating dark matter particles.

1 Gamma-ray Astronomy with Cherenkov Telescope Array

Gamma-ray astronomy is an exciting research field to study the very high energy phenomena in the Universe. The very energetic processes are opposed to thermal emission processes that originates from the random movements of particles with a given temperature. Many astrophysical objects exist that emit a significant fraction of non-thermal energy and many of them are the most explosive phenomena in the Universe, like Gamma Ray Burst (GRB) and Active Galactic Nuclei (AGN).

The ground based observation of the most energetic phenomena in astrophysical objects through high energy gamma-rays is a young field. The first discovery of an astrophysical object (Crab Nebula) at teraelectronvolt (TeV) energies was achieved by the Whipple Observatory in Arizona in 1989. Since then, over 160 sources were detected demonstrating impressively the huge physics potential of this field and the maturity of the detection technique. However, it also became apparent that the performance of current instruments is not sufficient to exploit the rich physics potential. The answer of the high energy astronomy community to the need of a more sensitive and more flexible observatory is the Cherenkov Telescope Array (CTA).

CTA is designed to achieve an order of magnitude improvement in sensitivity in the energy range from \( \sim 80 \, \text{GeV} \) to \( \sim 50 \, \text{TeV} \) compared to currently operating instruments like VERITAS, MAGIC and H.E.S.S. These current telescope arrays host up to five individual telescopes, whereas CTA is expected to detect gamma-rays over a larger area with about 100 telescopes in the Southern hemisphere and about 20 telescopes in the Northern hemisphere. CTA is also expected to have a much wider energy range coverage, a larger field of view, and a greatly improved energy and angular resolutions. These possible improvements will allow exciting new insights in key areas of astronomy, astrophysics and fundamental physics.

Due to the expected higher sensitivity the CTA observatory will detect more than one thousand sources allowing for population studies of source classes like AGN. Thanks to an improved
angular resolution CTA will be able to perform very detailed morphological studies of extended sources. As a result of a wider energy range coverage and improved energy resolution CTA will help to do spectral studies of unprecedented accuracy, giving stringent information about the acceleration mechanism. Finally, owing to the large number of individual telescopes in the arrays, the observatory can operate with different pointing directions for different subsystems. For example some telescopes point to a distant galaxy and at the same time some other group of telescopes observe a Galactic source.

CTA will be the first open very high energy observatory, providing data products to the scientific community after some limited proprietary period. CTA aims moreover to play a key role in multi-wavelength and multi-messenger astronomy with tight collaborations between the different gravitational wave, neutrino, cosmic-ray, space and ground based electromagnetic telescope communities.

The CTA consortium is presently composed of 1350 members working in 210 institutes from 32 countries. These group of institutions are responsible for directing the science goals of the observatory and the array production.

2 Imaging Atmospheric Cherenkov Technique

Gamma-rays interact with the Earths atmosphere and cannot be directly detected on the terrestrial surface. Gamma-rays are therefore either directly observed from space using detectors on satellites or indirectly from ground by detecting the electromagnetic showers that are generated by gamma-rays interacting with the Earth atmosphere.

The typical astrophysical sources have a gamma-ray flux which is \(dN/dE \approx E^{-2}\). Therefore, the gamma-ray detection area has to be increased with gamma-ray energy to compensate for the fast power law decrease of the gamma-ray flux with increasing energy. Due to the low flux of gamma-rays above 100 GeV, detectors for such energies require a large detection area, ruling out space-based detectors with detection area of typical size of about 1 m\(^2\). These satellite telescopes cannot collect a statistically significant number of such high energy gamma-rays events in an reasonable amount of time. The gamma-ray satellite telescopes like INTEGRAL\(^7,8\), COMPTEL\(^9\), Agile\(^10\) and Fermi\(^11\) are sensitive to energies of few tens of keV up to few hundreds of GeV. At higher energies two types of ground based gamma-ray instruments with different detection techniques exist. The first type of instruments observes the Cherenkov radiation that is produced by ultra-relativistic particles in an electromagnetic shower. Such instruments are called imaging atmospheric Cherenkov telescopes. The second type of instruments observes the particles of the electromagnetic shower when they reach the ground level, like the HAWC\(^12,13\) detector.

The aim of the imaging atmospheric Cherenkov telescopes is to take an image of the Cherenkov light produced in the Earth’s atmosphere as presented schematically in figure 1. When a very high energy gamma-ray interacts with an atmospheric nucleus usually produces an electron-positron pair. The electron-positron pair in turn can interact with the atmosphere and generate a cascade of particles (usually called electromagnetic shower) which are mostly electrons and positrons of lower energy. The shower develop down in the atmosphere following certain general geometric properties. The shower typically measure several kilometers and have a width of some hundreds of meters. Some of the shower particles travel at ultra-relativistic speed and emit Cherenkov light. This Cherenkov light propagates nearly unattenuated to the ground producing a faint pool of Cherenkov light of about 120 m in radius with a duration of a few nanoseconds. The effective detection area is at least the size of the pool of Cherenkov light on the ground, which is of the order of \(10^5\) m\(^2\). The optical mirrors of the telescopes reflect the collected Cherenkov light into the focal plane where a fast camera records the shower image.

The image in the camera represents the electromagnetic shower and is used to identify the primary cosmic gamma-ray. However, Cherenkov light is not only produced by gamma-rays
but also by hadronic cosmic rays. The shape, intensity and orientation of the image provides information about the primary particle type, energy and direction of the propagation. The elliptical shape of the gamma-ray image and the direction is the main feature to discriminate them against the overwhelming hadronic cosmic ray background which produce wider and more irregular images.

3 Reconstruction Methods

Reconstruction methods are used to separate the cosmic gamma-ray showers from the overwhelming hadronic cosmic ray showers. This separation is crucial for Cherenkov telescopes and is based on the different image pattern.

The current methods used to separate signal and background in Cherenkov telescopes arrays are largely based on two approaches. The first approach uses the combination of an extended Hillas parameterization of the detected shower images with multivariate classification methods, like random forest. The second approach fits the image to the result of a fast simulation under the hypothesis that the image is an electromagnetic shower. Although quite successful, both methods have some potential drawbacks. For the first one, the chosen parameters are not necessarily the best ones to deal with the signal and background separation problem, whereas for the second one the method is computationally very expensive.

Other approaches are currently under investigation, one of them is to study a deep network to deal with the signal and background separation problem, and related problems, like energy and arrival direction reconstruction. On one hand deep network work by constructing an optimal and compact representation of the shower image that can be used to perform classifications. On
the other hand deep networks work also as a reconstruction of the image under the assumption it belongs to the class of the image. Therefore deep networks seem ideal to merge the two approaches currently used with a computational cost during usage of the network close to the Hillas parameterization approach.

Currently machine learning techniques using TensorFlow are developed consisting of an image processing algorithm that can separate gamma-ray events from hadron events exploiting the full image recorded by the Cherenkov telescope on a pixel-wise information. A better classification of the images with respect existing methods could represent a major step forward in the field of observational gamma-ray astronomy. Parallel to the the use of novel high level reconstruction strategies, the development of new hardware which is presented in section 5, can boost the scientific performance.

4 Objective of Future CTA Project

The present Cherenkov telescope arrays have achieved very exciting results. These instruments are sensitive in an energy range range of $\sim 80$ GeV to $\sim 50$ TeV, have a typical field of view of 3 degree to 5 degree, their angular resolution is about 0.05 degrees above 1 TeV and the energy resolution is about 10% well above the threshold. Nevertheless the future CTA projects should improve the performance of the existing instruments.

For example, no gamma-ray source has so far been detected by present telescopes in the energy domain above 100 TeV. Extending the observation in the ultra-high energy domain will allow to understand the acceleration mechanism in galactic objects and help to discriminate between hadronic and leptonic models. On the other side of the energy spectra, lowering the energy threshold will be extremely important for the observation of distant extragalactic sources because the gamma-ray flux at higher energies is attenuated by the interaction with the extragalactic background light. In addition, a wide field of view combined with arc minutes angular resolution will allow efficient surveys and the study of extended sources.

The main objective of the future CTA project is to allow very high energy gamma-ray astronomy to transit from source discovery to detailed source investigation. To reach this goal CTA will be an observatory aiming to:

- Extend the energy range from about 20 GeV to about 300 TeV, providing to detect high redshifts objects and extreme accelerators.
- Increase the sensitivity by an order of magnitude at 1 TeV, providing the possibility to detect many new sources.
- Improve angular resolution down to few arc minutes, increasing rejection of hadronic background and improving the sensitivity.
- Improve energy resolution, facilitating spectral studies to constrain acceleration mechanism.
- Widen the telescope field of view, improving surveying capabilities and facilitate the study of extended sources.
- Increase the detection area and therefore photon rate, providing access to observe fast transient phenomena.
- Provide the access to the full sky.
5 CTA Concept with Mixed Size Telescopes

The CTA concept is artistically presented in figure 2 for a possible layout configuration. To optimize cost rather than to put one type of a given size Cherenkov telescope on a regular distance, the CTA concept consists in to use a mixed size telescope approach. During the design phase the mixed size telescope approach has been optimized under the constraints given by cost limits and scientific requirements.

CTA will be build with three different size of telescopes to cover the full energy range in a cost effective way. The large sized telescopes (LSTs) are optimized for energies from the lowest threshold to a few 100 GeV, the medium sized telescopes (MSTs) for the medium energy range from about 100 GeV to about 10 TeV, and the small sized telescopes (SSTs) for the highest energy range above a few TeV. A schematic view of the sizes of the different telescope types can be appreciated in figure 3.

In order to record a clean image of a gamma-ray shower, a fast sampling of the signal is required for all telescopes. The signal integration time has to be as short as the Cherenkov light flash duration which is of the order of a few nanoseconds. All telescopes have in the focal-plane a camera, which use different numbers of very sensitive sensors for the detection of Cherenkov light. The camera contains the readout electronics and it is connected to the data acquisition system by Ethernet optical fibers.

5.1 Large Size Telescope

The LSTs are the largest CTA telescopes, and are optimized to detect the lowest energy gamma-rays. Since event rates are high and systematic effect of the background limit the achievable sensitivity the detection area of these telescopes can be relatively small. The low energies gamma-rays are efficiently detected by four closely placed LSTs, with a mirror diameter of about 23 m and a focal length of 28 m. Such large mirrors are needed to collect as many Cherenkov photons as possible from the low energy showers. In order to discriminate the faint flashes produced by the lowest energy gamma-rays from the light of the night sky the LST camera is the fastest and most sensitive one in CTA. The LST will be supplied by a 1855 pixels camera with about
Figure 3 – Schematic view of three different sized telescopes optimized for three different energy ranges. On the left three different small size telescopes are shown: the first two are based on the Schwarzschild-Couder reflectors and the next one is based on the Davis-Cotton optical design. The primary mirrors have a diameter of about 4 m. In the middle a medium size telescope with a 12 m diameter Davis-Cotton mirror is depicted. Finally, on the right the design of the large size telescope with a parabolic dish of 23 m diameter is presented.

4 degree full filed of view. The large mirror area together with up to 40% quantum efficiency of the photomultipliers (PMTs) in the focal-plane camera and sophisticated trigger and readout logic provides LSTs to detect gamma-rays down to 20 GeV. This low energy range is extremely relevant because it allows the detection of the extragalactic gamma-ray sources like AGNs and of the sources with a limited acceleration power like pulsars.

In addition, the LST should also allow the discovery of gamma-ray emission in GRBs. These telescopes require therefore a short repointing time to allow quick follow-ups of GRB alerts. The LSTs should be able to reposition to any direction in the sky in less than 20 seconds after receiving an alert from a GRB monitor. In order to achieve a large size and light weight, the telescope structure is made of carbon fiber according to the approach followed by the MAGIC collaboration.

An artistic impression of the LST in comparison to the other telescopes is given in figure 3. The cost of each LST is about eight million euros and the first one will be also a prototype which will most probably be tested during 2018.

5.2 Medium Size Telescope

The energy range of about 100 GeV to about 10 TeV is covered by an array of MSTs with spacing of about 100 m. The shower detection and reconstruction in this energy range is based mostly on the experience of H.E.S.S. and VERITAS collaborations. The MST has a mirror diameter of about 12 m and a focal length of 16 m with a field of view of about 8 degrees. Improved sensitivity compared to current facilities will be obtained mainly due to increased area covered by the array and by the larger number of telescopes reconstructing a shower. The prototype MST shown in figure 4d is a modified Davies-Cotton telescope with a PMT-based camera. Two variants of signal readout are envisaged for the camera, the first one is the NectarCam and the second one is the FlashCam. The NectarCam is a 1855 pixel camera sampling pulses with
a nominal frequency of 1 GHz using ASICs. The FlashCam is a 1764 pixel camera sampling signals with Flash-ADCs at a rate of 250 MHz and digital trigger. In addition an alternative design is being developed, consisting on a dual-reflector Schwarzschild-Couder configuration and silicon sensor camera comprising of 11328 pixels. This design should have an improved performance, but is more technically challenging than the existing prototype MST.

5.3 Small Size Telescope

The high energy range with showers with energy above 10 TeV are detected by an array of SSTs. The main limitation for the detection of high energy showers is the number of gamma-ray showers per time and area. Consequently, the array needs to cover an area of several square kilometers to achieve a large statistic of high gamma-ray showers. At highest energies the light yield of a shower is large, so that showers can be detected even by small mirrors. Three different projects for the SSTs have been developed: two dual reflector solutions on the Schwarzschild-Couder optical system (SST-2M ASTRI and SST-2M GCT) and one based on single reflector on the Davis-Cotton optical design (SST-1M). These three prototypes are presented in figure 4a, figure 4b and figure 4c. The primary mirrors have a diameter of about 4 m and the field of view is about 9 degrees. The telescope ASTRI and SST-1M will be equipped with a silicon sensor camera, whereas the GCT camera can use either PMTs or silicon sensors.

6 Full Sky-coverage and Possible Array Layouts

Access to the full sky is important as many of the objects to be studied by CTA are rare. In order to have a full sky-coverage, the CTA observatory will provide two arrays, with sites in both hemispheres.

The Northern hemisphere array will have an area of of radius 0.4 km and will be optimized in
the energy ranges from $\sim 20$ GeV to $\sim 20$ TeV. This array is mainly dedicated to the observation of the northern extragalactic objects. Note that the absorption of high gamma-rays due to extragalactic background light can be large for extragalactic source so that no gamma-rays above few TeVs are expected. The Southern hemisphere array with an area of radius 1.5 km will span the entire energy range, covering energies from $\sim 20$ GeV to $\sim 300$ TeV. A possible design for the southern site is presented in figure 2. The southern array will give the opportunity to observe the galactic sources, in particular the Galactic Center, and the southern extragalactic objects.

The plan for the southern site is to host the three sizes of telescopes to cover the full energy range, whereas the northern site will most probably be equipped with only LSTs and MSTs. The Northern observatory will be made up of a 19-dish array (4 LSTs and 15 MSTs) and a 99-dish array (4 LSTs, 25 MSTs and 70 SSTs) distributed over several square kilometers will be placed in the Southern observatory. The possible layout of the two CTA arrays are shown in figure 5. The expected lifetime of the observatory is about 30 years.

7 Expected Performance of CTA

The expected performance of CTA has been derived through extensive Monte Carlo simulations taking into account many different possible array layouts. The expected derived results are produced by the so-called prod 2 version of the Monte Carlo simulations and up to date results can be found in the following website.

The contribution of the full array together with the different types of telescopes to the sensitivity for point sources is presented in the figure 6 left. The improvements in sensitivity and the wider energy range with respect to current instruments are clearly visible. The sensitivity is computed requiring $5 \sigma$ detection in 50 hours of observation time with at least 10 gamma-rays, reaching a sensitivity of a few milli Crab (1 Crab Unit = $2.79 \times 10^{-7} \text{ m}^2 \text{s}^{-1} \text{TeV}^{-1} \times (E/\text{TeV})^{-2.57}$). The cross-over in sensitivity between LSTs and MSTs is seen at about 250 GeV and that between MSTs and SSTs is at about 4 TeV. At these cross-over points, the combined sensitivity is almost a factor of two better than that of the individual components. For low energies, the rejection of hadronic showers is poor and the background dominates the signal. For high energies, the backgrounds are at a very low level and the point source sensitivity is only signal limited, due to the low rate of signal events.

The expected point source differential sensitivity for both southern and northern arrays for
Figure 6 – Left: Point source sensitivity for the full array layout (black line, filled squares). The full array sensitivity is compared to that of the different telescope types: 4 LSTs (red line, filled circles), 25 MSTs (green line, filled triangles), and 75 SSTs (blue line, upside down triangles). For comparison the current instruments sensitivity for the same observation time is shown (black line). Note that evolution of the sensitivity is expected as analysis algorithms improve and the final layout is fixed. Right: Point source differential flux sensitivity for CTA southern array (black solid line) and CTA northern array (blue dotted line). For comparison H.E.S.S.\(^{18}\), VERITAS\(^{39}\) and MAGIC\(^{40}\) sensitivities for the same observation time are shown. Also presented is the HAWC sensitivity\(^{41}\) for an observation time of one year and five years, together with 10 years Fermi-LAT sensitivity with two different levels of diffuse gamma-ray background radiation.

an observation time of 50 hours is compared in figure 6 right. Also shown are the sensitivities of MAGIC, VERITAS and H.E.S.S. for the same observation time. HAWC sensitivities are shown for an observation time of one year and five years, together with ten years Fermi-LAT sensitivity. The presented sensitivities give only an indicative comparison of the sensitivity of the different instruments, as the method of calculation and the criteria applied are different. The sensitivity of CTA southern array will be better than that of the northern side due to the higher number of telescopes and larger detection area. At energies above few TeVs the sensitivity of the southern array is increased due to inclusion of the SSTs. Nevertheless both arrays will outperform all existing detectors over the full energy range from about 50 GeV to about 100 TeV.

At the lowest energies and for steady sources, CTA will be worse than the Fermi-LAT sensitivity\(^{41}\), due to that Fermi-LAT has a much higher background rejection. However, for short-time phenomena, such as gamma-ray bursts or AGN flare, CTA will be several orders of magnitude more sensitive than Fermi-LAT even at lower energies, due to the larger effective detection area of CTA compared to Fermi-LAT. It is expected that CTA will be an ideal tool for transient phenomena, probing sub-minute-timescale variability.

In present arrays with at most five telescopes spaced by about 100 m, most of the detected showers have impact points outside the footprint of the array. The consequence is that the showers are detected usually by only one or two telescopes giving a modest angular resolution. This resolution can be improved by selecting showers with larger number of telescopes. By increasing the number of telescopes over a larger areas than the size of the Cherenkov light pool the showers are contained inside the telescope array. By selecting gamma-ray showers detected simultaneously by many of the telescopes, CTA can reach angular resolutions of better than 0.05 degrees for energies above \(\sim\)1 TeV as seen in figure 7 left. Note however that for this figure the result is not optimized to provide best angular resolution, but rather best point source sensitivity. Therefore higher resolution is possible at the expense of some detection area.

Figure 7 right shows the energy resolution defined as the half width of the \(\pm 34\\%\) interval around the most probable reconstructed energy, divided by the most probable reconstructed energy. The presented expected performance are based on the combination of Hillas parameterization and multivariate classification methods. Some improvement is expected with the use of more sophisticated techniques fully exploiting pixel-wise information as mentioned in section 3.
8 Science Themes

CTA will explore questions in physics of fundamental importance, with considerable potential for major discoveries in astrophysics. Some selected science themes of the CTA observatory are:

1. Understand the origin of relativistic cosmic particles.
2. Understand the role of the relativistic particles play in the evolution of star forming systems and galaxies.
3. Probe extreme environments such as neutron stars, black holes as well as cosmic voids.
4. Explore frontiers in physics such as the nature of dark matter.

The science themes of the CTA array are described in detail in the “Science with CTA” document, which is about to be published. There is a plethora of CTA science and only some selected results have been shown during the presentation, like the study of galactic and extragalactic acceleration mechanism as well as the observation of the long and short time variable phenomena. Figure 8 left shows the expected spectra for different emission scenarios simulated for a typical galactic source. The curves show a clear discrepancy detected at high energies according to different gamma-ray emission. The ambiguity between leptonic and hadronic processes can be nearly completed resolved at gamma-ray energies around 100 TeV. This is due to the Klein-Nishina effect, where leptonic emission is highly suppressed at energies above few tens of TeV.

In addition, CTA is perfectly suited to study cosmological effects on gamma-ray propagation. Results of different studies to probe extragalactic background light, intergalactic magnetic field, axions and Lorentz invariance violation have been presented. The main point is that by studying several sources at different distances, one can better disentangle intrinsic properties from photon propagation properties.

Finally, many theories predict that dark matter particles could annihilate each other and emit gamma-rays that CTA should detect and expected sensitivities from such indirect dark matter searches have been presented. The indirect search method looks for gamma-ray emission in astrophysical regions with a high dark matter density. The balance between the strength of expected dark matter annihilation signal, its uncertainty, and the strength of the astrophysical
Figure 8 – Left: Comparison of the spectral energy distribution from different gamma-ray emission. The black squares are the total of the fluxes for a leptonic and hadronic emission. The solid line shows the input spectra of gamma-ray simulation. The dotted line is for the case when the emission is purely leptonic. Right: The annihilation cross section $\langle \sigma v \rangle$ as a function of dark matter mass. The measured cross section sensitivities of H.E.S.S. and Fermi-LAT (blue) are compared to the CTA expected sensitivities curves for Galactic Halo (black), dwarf galaxy Sculptor (red) and Large Magellanic Cloud (green) using 500 hours of observation. The predicted curves have been calculated using the Navarro-Frenk-White dark matter profile and $W^+ W^-$ annihilation modes. One can see that, CTA will reach the expected gamma-ray emission from annihilation of dark matter particles with masses from a few 100 GeV to few TeV, provided that their annihilation cross section corresponds to the thermal relic density value.

9 Conclusion

The achievements of the very high energy phenomena in the Universe over the last three decades, fully justify the further exploration of the sky at these energies. The answer of the very high energy astronomy community is the Cherenkov Telescope Array, a next generation, more sensitive and more flexible facility. CTA, with a sensitivity increase of a factor about ten with respect to current telescopes, will reveal thousands of very high energy gamma-ray sources. One of the key features of CTA will be to extend the energy range from a few tens of GeV to above 100 TeV. The construction of the first telescopes has already started and working prototypes for small and medium size telescopes exist. CTA will operate as open astronomical observatories with exciting science in both hemisphere.

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