The CTA Observatory

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In recent years, ground-based very-high-energy (VHE; $E \gtrsim 100$ GeV) γ -ray astronomy has experienced a major breakthrough with the impressive astrophysical results obtained mainly by the current generation experiments like H.E.S.S., MAGIC, MILAGRO and VERITAS. The ground-based Imaging Air Cherenkov Technique for detecting VHE γ -rays has matured, and a fast assembly of inexpensive and robust telescopes is possible. The goal for the next generation of instruments is to increase their sensitivity by a factor $\gtrsim 10$ compared to current facilities, to extend the accessible γ -ray energies from a few tens of GeV to a hundred TeV, and to improve on other parameters like the energy and angular resolution (improve the point-spread function by a factor 4-5 w.r.t. current instruments). The Cherenkov Telescope Array (CTA) project is an initiative to build the next generation ground-based γ -ray instrument, will serve as an observatory to a wide astrophysics community. I discuss the key physics goals and resulting design considerations for CTA, the envisaged technical solutions chosen, and the organizational and operational requirements for operating such a large-scale facility as well as the specific needs of VHE γ -ray astronomy.

1. INTRODUCTION

Very-high energy (VHE) γ -rays are produced in nonthermal processes in the universe, namely in galactic objects like pulsars, pulsar-wind nebulae, supernova remnants (SNR), binary systems containing compact objects, or OB associations. Among the extragalactic VHE γ -ray sources are active galactic nuclei (AGN), particularly blazars and radio-galaxies, and starburst galaxies. Galaxy clusters and gammaray bursts are also potential, although not vet discovered, sources of VHE γ rays. Apart from the astrophysics of specific astronomical objects, γ -ray astronomy can be used to search for the annihilation of dark matter particles, and for studying the transparency and history of the universe. Further fundamental physics searches, like for the violation of Lorentz invariance, can be performed. For recent reviews, see, e.g., [1, 2].

Upon reaching the Earth's atmosphere, VHE γ -rays interact with atmospheric nuclei and generate electromagnetic showers. The showers extend over several kilometers in length and few tens to hundreds of meters in width, and their maximum is located at 8-12 km altitude, in case of vertical incidence. At VHE, the shower particles are stopped high up in the atmosphere, and can not be directly detected at ground. A sizeable fraction of the charged secondary shower particles, mostly electrons and positrons in the shower core, move with ultra-relativistic speed and emit Cherenkov light. This radiation is mainly concentrated in the near UV and optical band and therefore passes mostly unattenuated to the ground, with

minor losses due to Rayleigh and Mie scattering and Ozone absorption. Imaging atmospheric Cherenkov telescopes reflect the Cherenkov light onto multi-pixel cameras that record the shower images. The technique was pioneered by the Whipple experiment, which first detected the Crab Nebula in TeV γ -rays, in 1989.

2. CURRENT FACILITIES

Currently, the world largest ground-based IACTs are H.E.S.S., MAGIC and VERITAS.

H.E.S.S. is an array of 4 identical 12-m diameter telescopes, located in Namibia and operating since 2003. A fifth telescope of 28 m diameter, is under construction in the center of the array, and its completion is foreseen for 2010.

MAGIC, has been operated since 2004 as 17-m diameter single-dish telescope on the Canary Island if La Palma, Spain. Despite the use of a single reflector does not guarantee the sensitivity of an array, its large reflector surface of 239 m² allowed to reach the lowest energy threshold among the ground-based instruments, enabling for the first time observation below 100 GeV with this imaging air Cherenkov technique. A second MAGIC telescope is now fully operational, and the use of the stereoscopic observation technique will allow MAGIC to reach a significantly improved sensitivity.

A more recent experiment was started in the Arizona desert in USA, following the successful experience of the Whipple experiment. VERITAS has soon reached the expected performance, with a sensitivity

comparable to H.E.S.S., and is starting to collect important scientific results.

3. TOWARDS A PRECISION GAMMA-RAY ASTRONOMY

Despite the achievements of current-generation Cherenkov telescopes [1], there are limitations that future instruments will need to overcome: current instruments are sensitive in an energy range of \gtrsim 80 GeV-50 TeV. At the low energy end, systematic limitations come from the background from atmospheric hadronic (and electronic) showers. At the high end, the limit is statisticsi due to the too small collection areas at the high (multi-10 TeV) energies). telescopes is limited to a typical field of view (FOV) of $3-5^{\circ}$ diameter, as is the angular resolution, currently around a few arcmin. Also, current facilities are rather poorly automatized. From a physics point of view, there are strong arguments to improve in the following aspects: decrease the energy threshold to few tens of GeV; acquire sensitivity beyond 50 TeV; increase sensitivity in the core range (100 GeV-50 TeV); improve energy and angular resolution. Cherenkov Telescope Array (CTA) is a next-generation ground-based project which aims at implementing all these improvements.

4. CHERENKOV TELESCOPE ARRAY

The success of ground based γ -ray astronomy experiments in recent years has brought nearly all scientists working in the field in Europe together to design and promote CTA. This instrument will achieve superior sensitivity by deploying a large number of Cherenkov telescopes of different sizes covering a large area on the ground for high detection rates. CTA foresees improvement of sensitivity of factor 5-10 in the current energy domain (somewhat below 100 GeV to some 10 TeV) and will extend the energy range from 10 GeV to about 100 TeV (Fig. 1). The observatory will consist of two arrays: a southern hemisphere array, which allows deep investigation of galactic sources and of the central part of our Galaxy, but also for the observation of extragalactic objects. The northern hemisphere array is dedicated mainly to northern extragalactic objects. Obviously the arrays will not be only restricted to pure astrophysical observations, but will also make contributions to the field of particle physics and cosmology.

CTA will be operated as an open, proposal-driven facility analogous to optical observatories, that shall be available for all scientists from those countries that contribute to the construction and operation of the observatory. It is foreseen to follow the practice of

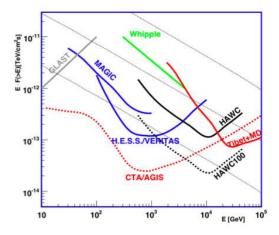


Figure 1: Integral sensitivity for a Crab-like spectrum for several current imaging air Cherenkov telescope facilities and expected for CTA and the Advanced Gamma-ray Imaging System; cf. [2]), a similar US-based project $(5\sigma, 50 \text{ h})$ and Fermi-LAT $(5\sigma, 1 \text{ yr})$.

other major, successfully operating observatories (e.g. the European Southern Observatory) and announce calls for proposals on regular intervals which will be peer-reviewed by a changing group of international experts. Based on experience of current experiments and other ground-based observatories, different classes of proposals (targeted, surveys, time-critical, Target of Opportunity and regular programs) are foreseen. User support will be provided via a data centre, in the form of standard processing of data and access to the standard MC simulations and analysis pipelines used in data processing.

5. SCIENTIFIC MOTIVATION

5.1. Low-energy physics (sub-50 GeV)

MAGIC has opened the field of ground-based sub-100 GeV γ -ray astronomy [3]. Observations with higher sensitivity in this region will have important consequences for galactic and extragalactic physics. By studying the sub-50 GeV energy band, CTA could provide the final answer to the acceleration mechanism in pulsars. A high sensitivity in the low energy regime is also vital for studying AGNs, which typically exhibit rather steep power-law spectra (due to the increasing suppression of γ -ray flux with energy by the extragalactic background light). Further, lowenergy sensitivity is vital to complement the catalog of Fermi-LAT detected γ -ray emitters with a possibly larger significance than obtainable by LAT at its high-energy end. This will provide a unique way to understand the nature of the tens of yet unidentified Fermi-LAT detected sources [5]. Also, γ -rays in the E < 100 GeV regime will help the broad-band mod-

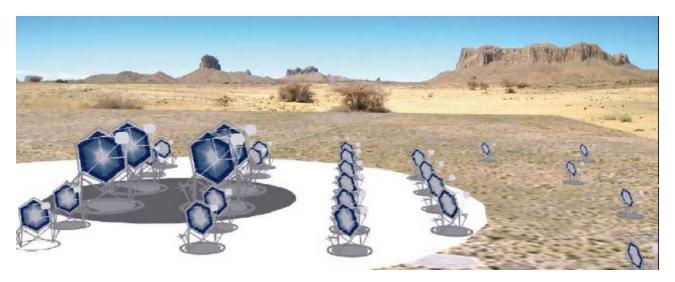


Figure 2: Artist's view of the composite CTA observatory. The area covered amounts to $1-10 \text{ km}^2$.

elling and thus to distinguish between the two basic classes of acceleration models, i.e., leptonic and hadronic acceleration models.

5.2. High-energy physics (above 50 TeV)

Typical astrophysical γ -ray spectra have bimodal distributions with one peak at lower energies due to synchrotron emission, and a second peak at higher energies due to inverse Compton scattering of VHE electrons on seed infrared/optical photons. For galactic objects, one may expect to observe VHE powerlaw γ -ray spectra with cutoffs due to intrinsic mechanisms. γ -rays from distant blazars suffer a severe attenuation after pair production with local IR-UV photons of the extragalactic background light (EBL). In all current IACT data, the evidences for spectral cutoffs and steepening are rather poor. There is no simple justification for this. CTA will explore this region with unprecedented sensitivity. This will allow to understand the acceleration mechanism in galactic objects like SNRs, and discriminating hadronic/leptonic models. The high energy region is also important for identifying PeVatrons, i.e. cosmic-ray accelerators to TeV/PeV energies. Detecting outbursts ("flares") from distant AGNs at super-TeV energies would allow to increase the prospects for firm limits on Lorentz invariance violation.

5.3. Core energy region (0.1-50 TeV)

CTA will provide an increase of the sensitivity in this core energy region by at least a factor 10 as compared to the current IACTs, reaching a level of 10^{-3} C.U. sensitivity in this range. (The differential photon flux of the Crab nebula between 60 GeV and 9 TeV is [4] $dF/dE = (6.0 \pm$

 $0.2)10^{-10}(E/300\,\mathrm{GeV})^{a+b\log_{10}(E/300\,\mathrm{GeV})}\,\mathrm{TeV^{-1}cm^{-2}s^{-1}}$ with $a=-2.31\pm0.06,\,b=-0.26\pm0.07.)$ This will promote γ -ray astrophysics to a γ -ray astronomy. In fact, for the first time, CTA will allow for a full VHE sky survey, with approx. a thousand new VHE γ -ray sources expected to be detected.

An increase in sensitivity will, by reducing the required observation times, allow more follow-up observations and higher time resolution of variable sources. The current telescopes are sensitive enough to detect variations on timescalew of minutes. CTA will allow a sub-minute resolution, and thus to understand the complex phenomena of γ -ray flares, directly connected to the acceleration mechanisms and the local environment. Morphological studies will profit from reduced required observation times. These are of importance to study spatially extended γ -ray emitters, like SNRs. An increase of the angular resolution by a factor 4-5, down to 0.02 arcmins (current theoretical limits are discussed in [6]), will reduce source confusion and improve collaboration with instruments observing at other wavelengths.

6. GENERAL DESIGN IDEAS

maintain an overall high technical performance, the CTA concept (Fig. 2) is based on few general ideas: Increase the array from currently 4 (H.E.S.S., VERITAS) to ≈ 100 telescopes; distribute them over a large area (1–10 km²); make use of telescopes of 2–3 different sizes; take advantage of well-proven technology of current IACTs; high automatization and remote operation; run array as observatory and open the facility to the astronomy and astrophysics community.

7. General technical ideas on CTA

An increase in sensitivity over the full energy range can only be achieved by combining many telescopes distributed over a large area of at least 1 $\rm km^2$ and using telescopes of 2–3 different sizes: several medium size telescopes (MST) of 12 m, few large size telescopes (LST) of 24 m diameter, and probably several small size telescopes (SST) of 7 m diameter. The number of the telescopes, their size, configuration and the overall performance are under investigation.

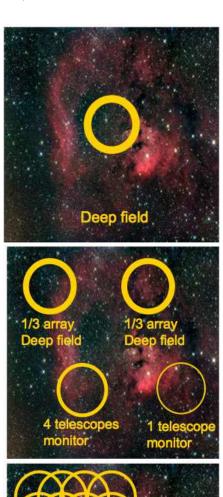
The LSTs detect sub-100 GeV photons thanks to their large reflective area. Technologically, they are the most challenging telescope type. A design is currently under development. Several tens of MSTs will perform the γ -ray detection in the core energy region. Those telescopes will be based on the experience gained with the H.E.S.S. and MAGIC telescopes. The main goal is to reduce cost and maintenance efforts. The MSTs constitute the core of the array, and will also perform the fundamental task of vetoing the LST triggers to reduce hadronic background. The MST design is currently studied and the construction of a prototype is expected in few years from now. In case 3 different telescope sizes are required, several tens of SSTs will complete the array to perform the super-TeV search, increasing the effective collection area of the array. Very simple in construction, contributing only a small percentage to the cost of the full array.

The trigger systems will support different operation modes (Fig. 3). In the "deep field" mode, all telescopes will be pointed to the same sky position to maximize the sensitivity. In a more flexible mode, parts of the telescopes could point to different positions, with few telescopes making follow-up observation of single sources as, e.g., to monitor blazar activity. Finally, the array can be operated in a "wide-FOV" mode, to perform an all-sky scan in a time-efficient way at a moderate sensitivity.

8. The CTA consortium

CTA is a partnership between the H.E.S.S. and MAGIC collaborations and several European institutes, with recent interests from more institutions world-wide. Activities are coordinated with AGIS (Advanced Gamma-ray Imaging System; cf. [2]), a similar US-based project. The consortium comprises > 70 institutes from 17 countries, involving more than 400 scientists.

For the current design phase, CTA is organized in several work packages: Management, Physics, Monte Carlo, Site, Mirror, Telescope, Focal-Plane Instrumentation, Electronics, Atmospheric Transmission and Calibration, Observatory, Data, and Quality Assurance. The telescope design and component prototyping are expected to be completed in 2011 and



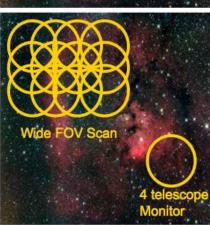


Figure 3: Possible operation modes for CTA. From left to right: deep field, flexible and wide field modes. More details in the text.

2012, respectively. Array prototypes could exist by 2012/13, and the construction of the full array and partial operation could be started in 2014/15.

9. SPECIFIC NEEDS OF VHE GAMMA-RAY ASTRONOMY

Like the major optical and radio observatories the CTA arrays will be situated in remote locations, which

means that the operation of the array should be as robotic as possible. On the other hand, the detection technique of Cherenkov telescopes require operation of high voltages, which makes the robotic operations challenging. It is also foreseen that the observations of a single source are distributed over several nights and on same night several sources from different proposals will be observed. Therefore the onsite operations i.e. the observations and maintainance will be handled by the onsite staff rather than visiting astronomers.

Another challenge will be the data rate from the foreseen 100 telescopes. The remote location will most likely not allow the real-time transfer of the raw data, but the data will rather be pre-processed onsite. The layout of the CTA observatory will consist of operations centre/centres, data centre, management and user community.

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