The Cherenkov Telescope Array

an advance facility for the ground-based high energy gamma-ray astronomy

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SciNeGHE 2010
Outline

- State of art of the Gamma-Rays Astronomy
- CTA: a new science infrastructure
- Realizing CTA
- Summary
State of the VHE gamma-rays astronomy

July 2010:
103 TeV sources
61 Gal. / 42 EG


RESULTS FROM HESS, MAGIC & VERITAS

From J. Hint, TeVPa 2010
Galactic Sources Population

Number of VHE Galactic sources

HD-Gamma08 (07/2008)
H.E.S.S. EGPS (01/2008)
Milagro GPS (08/2007)
H.E.S.S. GPS 2 (01/2006)
H.E.S.S. GPS 1 (03/2005)

Discovery date
Sep/97 Jun/00 Mar/03 Dec/05 Aug/08

(Renaud 2009)

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TYCHO

Vela Junior

RX J1713

HESS J1813–178

Vela X

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Extragalactic sources

- **Active Galaxies**
  - 33 BL Lacs (mostly HBL)
  - High Flux variability
  - FSRQ (3C279; PKS 1222+21; PKS 1510-089)
  - Radio galaxies
    - Cen A (core emission)
    - M 87 (days scale variability)
      Flare 2008.
    - IC 310 (recently detected by MAGIC & Fermi)

- **Starburst galaxies**
  - M82 VERITAS
    - $z = 0.0008$
    - Discovery 2009
  - NGC 253 HESS
    - $z = 0.0008$
    - Discovery 2009
The next generation of IACT arrays needs to function like a true observatory:
Observation time for astro-physical/particle community
Open access data at different levels
CTA: a new science infrastructure

The Concept
The Scientific Motivation & Potential
CTA as a revolutionary concept

- Advancing VHE Gamma-Ray Astronomy
- Unprecedented performance as an IACT instrument.
- European and international integration (Consortium)
- Operation as an open observatory
- New technical implementation, operation, and data access
Advancing VHE Gamma-Ray Astronomy

guaranteed high-energy astrophysics results & large discovery potential

Cosmic rays origin and interaction

- Origin and propagation of Galactic cosmic rays (only SNR?)
- Understanding of processes around pulsars, binary systems, PWN structure
- Starburst galaxies
- Signatures of UHECR acceleration sites?

Nature of the different types of black hole particle accelerators

- Detailed understanding of acceleration & emission processes in different classes of AGN
- Detection of VHE gamma rays from GRBs?

Beyond the Standard Model Physics

- Cosmology with VHE gamma rays (probing the EBL)
- Fundamental physics
  - Detection of Dark Matter?
  - Test Lorentz Invariance Violation
Unprecedented performance as an IACT instrument.

AGN & Pulsar Physics

Deep TeV Sky survey

10% Crab

Exploration of the EHE regime of galactic sources

1% Crab

10% Crab

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Expectations for galactic survey

- 300 sources in $-30^\circ \leq l \leq 30^\circ$

**HESS map of the Gal. plane, total exp ~500 hours**

**Simulated CTA map, flat exposure ~ 5 hours/field**

*Funk, Hinton, Hermann, Digel, arXiv0901.1885*

**SNRS:**
- CTA Galactic plane survey, currently known shell SNRs detectable to 10–15 kpc (i.e. throughout most of the Galaxy)
- If shells shine 2000 yr in TeV, ~40 TeV shells in Galaxy; ~25 detectable (vs 6 currently known)
- Gamma-Ray shell directly resolvable by CTA to 5–7 kpc
- More distant SNR shells identifiable through follow-up multi-wavelength observations (e.g. radio)

Y. Gallant, TevPa 2010
Expectations for galactic survey

~ 300 sources in \(-30^\circ \leq l \leq 30^\circ\)

HESS map of the Gal. plane, total exp \(~ 500\) hours

simulated CTA map, flat exposure \(~ 5\) hours/field

Funk, Hinton, Hermann, Digel, arXiv0901.1885

Pulsar Wind Nebulae

- CTA will detect luminous PWNe like the Crab to the distance of the Large Magellanic Cloud luminosity-limited survey
- If PWNe shine 10 000 yr in TeV, \(~ 200\) TeV PWNe in Galaxy (75% detectable by CTA)
- In a CTA Galactic plane survey, weaker PWNe like Kes 75 detectable to \(~ 13–15\) kpc (i.e. in large fraction of Galaxy)
- Identifiable through follow-up MWL observations (non-thermal X-ray nebulae, pulsar search)

Similar for other Galactic TeV γ-ray sources: Y. Gallant, TevPa 2010
binaries, SNRs interacting with molecular clouds, star forming regions. . .
Extragalactic studies with CTA: Active Galaxies, Cosmic Radiation Fields and Cosmology

- Study of different AGN classes at VHE (unification, "blazar sequence")
  - today: ~30 BL Lacs, 3 FSRQ, 3 radio galaxies,
  - Population studies, luminosity function today:
    - largely biased in redshift,
    - small statistics
  - Spectral features and variability
    - information on acceleration & cooling processes
    - hadronic vs. leptonic scenarios
    - constraints on emission region
  - Mapping of radio galaxies
  - Probing the EBL and the extragal. magnetic field
Extragalactic studies with CTA: Active Galaxies, Cosmic Radiation Fields and Cosmology

- Predicted AGN detectability using Fermi

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A. Zech Snowpac 2010

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Extragalactic studies with CTA: Starbursts Galaxies, GRBs, Dark matter searches

- **Starburst Galaxies**
  - VERITAS and H.E.S.S. have observed TeV gamma-rays from the nearest starburst galaxies.
  - Improved CTA sensitivity at higher and lower energies implies
    - understand the spectra, constrains on physical emission scenarios,
    - study the relationship star formation processes and gamma-ray emission

- **GRBs**
  - Fermi LAT → emission above 10 GeV (30 GeV) from 4 (2) GRBs
  - A good fraction observables by CTA:
    - Rapid observations (1’ reaction time) and a wide energy range
      - “capture” the SED
Extragalactic studies with CTA: Starbursts Galaxies, GRBs, Dark matter searches

- **Dark matter search**
  - DM can annihilate or decay to detectable gamma-rays. Large dark matter densities $\rightarrow$ detectable fluxes, (i.e. annihilation rate $\propto$ square of the density).
  - Galactic Centre
    - the most promising candidate to look for DM annihilation radiation.
      - Identification of dark matter complicated.
      - Angular and energy resolution of CTA + enhanced sensitivity $\rightarrow$ disentangle the different contributions to the radiation from the GC.
  - Other individual targets: dwarf spheroidals and dwarf galaxies.
    - Large mass-to-light ratios + low astrophysical backgrounds.
  - CTA will provide coverage for the highest-energy part of the multi-wavelength spectrum necessary to pinpoint, discriminate and study dark matter indirectly.
European and international integration

- Consortium formed by 22 countries
  - 16 European countries
  - Argentina, Armenia, Japan, Namibia, South Africa, United States
  - 100 institutions
  - 200 physicists and engineers
  - Regular general CTA meetings since 2006
  - spokesperson: W. Hofmann (MPIK Heidelberg)
  - co-spokesperson: M. Martinez (IFAE Barcelona)
CTA unprecedented scientific performance

- **Sensitivity**
  - A factor 10 more sensitive than current instruments

- **Spectral coverage**
  - A single facility covering three to four orders of magnitude in energy range.

- **Angular resolution**
  - A factor 5 better than what is typical for current instruments (arc-minute range)

- **Temporal resolution**
  - On sub-minute time scales.

- **Flexible operation modes**
  - Wide range of configurations (in-depth study of individual objects + monitoring tens of flaring candidates)

- **Survey capability**
  - Increase of sky area surveyed per unit time + full-sky survey at high sensitivity.

- **Global coverage and integration**
  - Two sites (North + South)
CTA basic layout

Low energy section
~1% Crab
$E_{th}=20-30$ GeV
24m telescopes (x 4)

Medium energies
mCrab sensitivity
100 GeV – 10 TeV
12m telescopes (x 28)

2 Sites: Northern (extragalactic sources)
Southern (galactic extragalactic sources)

High energy section
< 10% Crab
MultiTeV energies
5m telescopes (x 20)
Several operation modes

- Monitoring: 4 telescopes

- Survey mode: Full sky at current sensitivity in ~1 year

- Very deep field

- Deep field: ~1/3 of telescopes
CTA TELESCOPE layout

- **Field of view**
  - High energy array → large FoV mandatory
  - Low & intermediate array → not so trivial:
    - Detection of high energy showers at large impact distance without truncation
    - Efficient study of extended sources and diffuse emission regions
    - Large-scale surveys and parallel study of many clustered source
    - Larger FoV → growing number of photosensors and electronics channels.
  → Optically challenging

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*Focal ratio required as a function of the half angle of the FoV*

- **Spherical design**
- **Parabolic design with constant radii**
- **Davies-Cotton design**
- **Parabolic design with adjusted radii**
CTA TELESCOPE layout

- **Pixel size**
  - The gain of small pixels depends strongly on the analysis technique
    - classical second-moment analysis: $0.2^\circ - 0.15^\circ$
    - full image distribution: $0.06^\circ - 0.03^\circ$
  - Pixel size $\rightarrow$ influence on trigger strategies.
  - **Current simulations:**
    - $0.07^\circ$ for large size telescopes
    - $0.15^\circ$ for medium size telescopes
    - $0.25^\circ$ for small size telescopes

*Identical field-of-view γ-ray shower of 460 GeV*
CTA TELESCOPE layout

- **Signal shape and timing recording**
  - to reject backgrounds
  - to reduce the signal integration windows → reduce amount of NSB noise
- Variable and matched integration windows across the image
- Under study with the current MAGIC and VERITAS systems,

1 ns samples
10 TeV gamma shower
250 m core distance
Optics and pixels H.E.S.S.1
FoV of 10°
25 ns total
CTA TELESCOPE layout

- **Trigger strategy**
  - Multi-telescope trigger coincidence
  - Signals from different telescopes combined at the pixel level
  - Intermediate solutions:
    - trigger pre-processors extract image features
    - the system trigger decision includes this information.

- **Trigger topology**
  - Derived locally.
  - The central station take a global decision.

- **Trigger schemes**
  - multi-level hierarchy
    - first trigger level (pixels and pixel groups)
    - higher levels (image or telescopes morphology)
The Cherenkov Telescope Array

The Design Studies:
Performance
Telescope technology
Site selection

http://fr.arxiv.org/abs/1008.3703
CTA Design Studies

- **AIMS**
  - select the appropriate sites
  - reduce production costs of telescopes, sensors, electronics etc (technology already proven with HESS, MAGIC, VERITAS).
  - improve reliability of components and systems

**Working Groups**

**Performance & Physics**
- Monte Carlo simulations
- Physics

**Instrumentation**
- Telescope
- Mirrors
- Focal Plane Instrumentation
- Electronics
- Quality assurance

**Observatory Selection & Operation**
- Site Selection
- ATAC
- Data
- Observatory
Monte Carlo Studies

- Development & validation of simulation tools
  - Air showers simulators
    - Interaction models
    - Atmosphere treatment
    - Time consumed
  - Telescope simulators
    - Images reproduction
    - Accuracy on energy
    - Timing

Blazar PKS2155-304
2006 HESS data
High S/N \(\rightarrow\) almost not background
Inputs MC: measured spectrum, HESS optical efficiency, zenith angle
Monte Carlo Studies (Array configurations)

Benchmark array
9 telescopes

Hyper-array 275 telescopes

Sub arrays (under cost constraints)

B: compact distribution with large telescopes
Better performance at low energy

C: extended distribution with medium telescopes
Better performance at high energy

E: combination of both
Better performance at all energies

$O(10^{11})$ events generated: $O(10^2)$ TB data stored
Monte Carlo Studies (Sensitivity)

ALTITUDE

- 2000 m (red)
- 3500 m (green)
- 5000 m (blue)

Differential sensitivity [HEGRA C.U.]

Reconstructed energy [TeV]

PIXEL SIZE

- 0.28 deg.
- 0.20 deg.
- 0.14 deg.
- 0.10 deg.
- 0.07 deg.

Differential sensitivity [C.U.]

Energy (TeV)

DIFFERENT CONFIG.

CTA wished

$log_{10}(E/\text{TeV})$

$E \cdot \text{Integral Sensitivity (erg cm}^{-2} \cdot \text{s}^{-1})$

CONFIG. “E”

$E^2 \cdot dN/dE$ (erg cm$^{-2}$ s$^{-1}$)

-log_{10}(E/\text{TeV})

log_{10}(Energy/\text{TeV})

0.5h

5h

50h
MonteCarlo Studies (Angular & Energy Resolution)

Energy resolution < 30% all CTA range
10% for 1 TeV

Angular resolution for 1 TeV: 0.04°-0.05°

E* = using pixel timing info
CTA Technology (Telescopes)

- **MST**
  - Middle Size
  - 1500 pixels
  - 2.5 ton camera
  - f/d ~ 1.4

- **LST**
  - Large Size
  - 2500 pixels
  - 2 ton camera
  - f/d ~1.2

- **SST**
  - Small Size
  - 1300 pixels
Telescope Technology

- Mount & Dish
  - Mounting system & drivers
  - Dish design and camera support

- Telescope optics
  - Mirrors
  - Alignment system

- Photon detection
  - Electronics
  - Triggering
  - Camera integration

- Calibration and monitoring
CTA mirror studies

Baseline

- 10000 m$^2$ of mirror area !!!
- Focusing worse than astronomical mirrors
- Hexagonal shape
- Size: 1200 mm ± 2 mm flat to flat (MST prototype)
- Weight < 35 kg/m$^2$ (including AMC and fixations)
- Reflectance > 80% (300-600 nm)
- Spot size < 1 mrad (68% containment)
- Spherical with radius 30-40 m (MST), aspherical (LST)

Mirror production technology

- Grinding/polishing or milling
- Replica technique (mold)
CTA mirror developments

Diamond-milled aluminium

Carbon-fibre composite
SMC technology

Open fibre-reinforced plastics

Carbon-fibre composite with CFRP honeycomb

Cold slumped glass-foam sandwich
CTA Mirrors evaluation

Old foam mirror

Saclay - carbon

HESS

•x average deviation from mold shape

-0.05  0.0  0.05  0.1

1st Cycle  2nd Cycle  3rd Cycle  4th Cycle

Glass

Aluminium

Carbon Fiber

G10

Wait until mirrors cool

“hot” mirrors
CTA Site Search

Not so high (<1500 m) / No sysmik risk / More than 60% of clear days (until 2025) / Nice aiire temperatures (~20°C) / Not so windy

Reduced list of candidates

Good place to live?

Local measurements
Dedicated instruments

Good place to live?
Realizing CTA: open observatory

Organisation
Operation
Time Schedule
Project Phases

- **Design Study:**
  - definition of the layout of the arrays,
  - telescope types,
  - design of the telescopes and small-scale prototyping.

- **Prototyping and Preparatory:**
  - prototyping and deployment of full-scale telescopes,
  - preparation of the construction and installation,
  - solving technical, organizational and legal issues,
  - site preparation.

- **Construction:**
  - construction,
  - deployment and commissioning of telescopes.

- **Operation:**
  - operation as an open observatory
  - calls for proposals and scheduling,
  - operation and maintenance of the facility,
  - processing of the data and provision of analysis tools.
### Time Schedule and costs

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**Design study**

- **FP7 Prep. Phase**: 5.2 M€

**Additional Costs**

- **100M€ Southern Obs.**
- **50M€ Northern Obs.**

![Conceptual design report](image)
CTA Operation as an open observatory
Summary and outlook

☑ CTA will be the major observatory in VHE gamma ray astronomy in the 2020s with both guaranteed astrophysics and a significant discovery potential.

☑ CTA received excellent reviews and high rankings in Science Roadmaps in Europe and across the world.

☑ CTA is an acknowledged ESFRI project & features high on roadmaps of future projects of ApPEC, ASPERA and ASTRONET.

☑ The CTA design study is aiming at reducing costs and improving reliability of instruments and systems.

☑ It is still on-going, with significant advances in mirror technology, telescope design (MST), electronics.

☑ The FP7 Prep. Phase for CTA should start in 2010 (duration 3 years).
THANKS!
Backup slides
CTA operation as an open observatory

- Scientific program steered by proposals
  - measurements of specific objects
- Observations according to observing proposals selected for scientific excellence by peer-review
- Limited number of outstanding proposals from scientists working in institutions outside the CTA-supporting countries
- All data obtained by the CTA accessible to scientists outside the proposing team after a finite period.
- CTA observations conducted by a dedicated team of operators.
CTA mirror studies

Mirror production technology

grinding/polishing or milling

- Glass mirror
  HEGRA, CAT, H.E.S.S., VERITAS
  machined and polished glass blanks
  Aluminium coated protection layer of SiO₂
  high reflectivity
  good PSF
  Fragile, heavy
  fast ageing and degradation

- Diamond-milled aluminium mirrors
  MAGIC
  Sandwich: 2 thin aluminium layers & an aluminium honeycomb
  Rigid, light
  high T conductivity
  Slow degradation
  Low reflectivity

- Cold slumped glass mirrors
  two thin glass sheets glued on a suitable core material.
  Front glass sheet formed on a master using vacuum suction
  Thermal insulation

- Aluminium foil mirrors
  Aluminium honeycomb sandwich
  2 thin Al sheets
  Imperfect reflection properties

- Fibre reinforced plastics mirrors
  Carbon or glass-fibre reinforced plastic
  Sandwich structure:
  Foam, honeycomb
  Expensive
  Low weight

replica technique (mold)
CTA wished sensibility and energy range

59 tel. config. “E” (without improved analysis or layout opt.) €80M nominal cost
AGN population

=> still many blazars to discover at TeV energies!

=> and maybe other types of AGN?
Blazars and Lorentz invariance

- Space-time at large distances is “smooth” but, if Gravity is a quantum theory, at very short distances it might show a very complex (“foamy”) structure due to Quantum fluctuations.

- A consequence of these fluctuations is the fact that the speed of light in vacuum becomes energy dependent.

- The energy scale at which gravity is expected to behave as a quantum theory is the Planck Mass

\[ E_{QG} = O(M_P) = O(10^{19}) \text{ GeV} \]
From a purely phenomenological point of view, the effect can be studied with a perturbative expansion. The arrival delay of $\gamma$-rays emitted simultaneously from a distant source should be proportional to the path $L$ to the source and the difference of the power $n$ of their energies:

$$\Delta t \sim \frac{E^n - E_0^n}{E_{QG}^n} \frac{L}{c}$$

The expected delay is very small and to make it measurable one needs to observe very high energy $\gamma$-rays coming from sources at cosmological distances.

Juan Cortina (IFAE)
Blazars and Lorentz invariance


LCs for different energy ranges
(4 min bins)

July 9

Flare is seen in all energy ranges

Time delay of 4 +/- 1 minute between highest and lowest energy ranges
Blazars and Lorentz invariance

If that delay would be fully caused by propagation in the vacuum then:
- for first order (n=1) =>
  \[ E_{\text{QG}} \sim \frac{M_p}{200} \pm 25\% \]

- for second order (n=2) =>
  \[ E_{\text{QG}} \sim 8 \times 10^9 \text{ GeV} \sim 7 \times 10^{-10} M_p \]

If delay had an astrophysical origin then the above numbers should be considered as lower bounds on the Quantum Gravity scale.
Most relevant: we provide the most stringent limits to date on Lorentz Invariance.

CTA: need larger sample for objects and higher sensitivity to access even faster variability.

Juan Cortina (IFAE)
Unprecedented performance as an IACT instrument.

CTA High-energy phenomena
✓ Galactic and extragalactic astrophysics
✓ Plasma physics
✓ Particle physics
✓ Dark matter
✓ Fundamental physics of space-time.
✓ Birth and death of stars
✓ Matter circulation in the Galaxy
✓ History of the Universe.
Extragalactic VHE $\gamma$-rays produce pairs when they interact with the **Extragalactic Background Light** (metagalactic field in the optical to far infrared range).
Absorption features in the spectra of blazars allow to determine the EBL in the mid IR range where no direct measurement is feasible.
Blazars and cosmology

- The EBL limits the maximum distance which a $\gamma$-ray of a given energy can travel, i.e., for each energy there is a “$\gamma$-ray horizon”.
- Lower threshold instruments like MAGIC are expanding this horizon but CTA may bring it well beyond $z=1$, into the bulk of the cosmological AGNs.

Measuring the EBL as a function of redshift sets important constraints to models of structure formation. And could be used to measure cosmological parameters. The cutoff energy provide an independent estimate of the distance to the sources.

Juan Cortina (IFAE)