The Cherenkov Telescope Array for VHE Astrophysics

Rene A. Ong (UCLA), for the CTA Consortium

HAWC Science Symposium, 26 March 2015
**Outline**

- **Scientific & Technical Motivation**
  - VHE sky and Existing Instruments
  - Imaging Atmospheric Cherenkov technique
  - Planning for the Future → CTA

- **Cherenkov Telescope Array (CTA) Concept**
  - Requirements & Drivers
  - CTA Design & Performance → Scientific Capabilities

- **CTA Implementation & Status**
  - Implementation: Telescope and Array Design

- **Synergies with HAWC (and other facilities)**
Scientific & Technical Motivation
Exploring the non-thermal Universe

- Pulsars/PWN: NS dynamo winds, Jets, winds
- SNRs: SN activity, Cosmic rays
- Starbursts: SMBH accretion, jets
- AGN: GRBs, Fermi Mech., Jets, winds
- GRBs: Unknowns (Gal Center)
- VHE $\gamma$-rays
- Dark Matter
- Cosmological Fields
- PBHs, QGr

Probing New Physics at GeV/TeV scale
VHE $\gamma$-ray Sky c2014

~150 sources

tevcat.uchicago.edu

Detailed source information: Spectra, Images, Variability, MWL …
VHE $\gamma$-ray Sky c2014

~150 sources

Detailed source information: Spectra, Images, Variability, MWL … + FERMI-LAT map
Complementary results from wide-field VHE telescopes:
e.g. Milagro, Tibet, ARGO-YBJ, IceCube

Portion of Milagro sky-survey near Galactic plane

Cosmic ray anistropy – confirmed by 3 experiments
VHE Telescopes (2013)
1st Interaction:

"Shower"

For \( E = 1 \text{ TeV} \) \( (E_{\text{C}} \approx 80 \text{ MeV}) \)

\( X_{\text{max}} \approx X_0 \ln \left( \frac{E}{E_{\text{C}}} \right) / \ln 2 \)

\( h_{\text{max}} = h_0 \ln \left( \frac{X_A}{X_{\text{max}}} \right) \)

\( X_0 \approx 5 \text{ km} \)

\( \left[ \text{pair} = \frac{9}{7} X_0 \approx 50 \text{ g/cm}^2 \right] \)

\( X_A = X_0 e^{-h_0/h_0} \)

\( X_A \approx 10^3 \text{ g/cm}^2 \)

\( h_{\text{pair}} = h_0 \ln \left( \frac{X_A}{X_{\text{max}}} \right) \)

\( \approx 20 \text{ km} \)

\( C_{(\text{max})} = \arccos \left( \frac{1}{n} \right) \approx 1.4^\circ \)

UV-optical reflecting mirrors focusing flashes of Cherenkov light produced by air-showers onto ns-sensitive cameras.
From current arrays to CTA

Light pool radius
$R \approx 100-15\text{-}m$
$\approx$ typical telescope Spacing

Sweet spot for best triggering & reconstruction...
most showers miss it!

✓ Large detection Area
✓ More Images per shower
✓ Lower trigger threshold
How to do better with IACT arrays?

➡ More events

- More photons = better spectra, images, fainter sources
  - Larger light collecting area
  - Better reconstructed events
- More precise measurements of atmospheric cascades and hence primary gammas
  - Improved angular resolution
  - Improved background rejection power

➡ More telescopes!

Simulation:
Superimposed images from 8 cameras
Planning for the Future

What do we know, based on current results?

Great scientific potential exists in the VHE domain
- Many more sources, much better understanding possible
- Much deeper probes of new physics

IACT Technique is very powerful
- Have not yet reached its full potential

Exciting science in both Hemispheres
- Argues for new facilities in S and N

Truly Astronomical facility $\rightarrow$ Substantial reward
- Open Observatory needed to get the best science
- MWL/MM connections are of critical importance
CTA is being developed by the CTA Consortium:

29 countries, ~1200 participants, ~180 institutes, ~400 FTE
Science Themes

**Theme 1: Cosmic Particle Acceleration**
- How and where are particles accelerated?
- How do they propagate?
- What is their impact on the environment?

**Theme 2: Probing Extreme Environments**
- Processes close to neutron stars and black holes?
- Processes in relativistic jets, winds and explosions?
- Exploring cosmic voids

**Theme 3: Physics Frontiers – beyond the SM**
- What is the nature of Dark Matter? How is it distributed?
- Is the speed of light a constant for high energy photons?
- Do axion-like particles exist?
Requirements & Drivers

**Energy coverage**
- Down to 20 GeV (Discovery domain: GRBs, Dark Matter)
- Up to 300 TeV (Pevatrons, hadron acceleration)

**Good energy resolution, ~10-15%:**
- (Lines, cutoffs)

**Large Field of view 8-10°**
- (Surveys, extended sources, flares)

**Rapid Slew (20 s) to catch flares:**
- (Transients)

**10x Sensitivity & Collection Area**
- (Nearly every topic)

**Angular resolution < 0.1°**
- Above most of E range (Source morphology)
CTA Design (S array)

Science Optimization under budget constraints

**Low energies**
Energy threshold 20-30 GeV
23 m diameter
4 telescopes (LST’s)

**Medium energies**
100 GeV – 10 TeV
9.5 to 12 m diameter
up to 25 single-mirror telescopes
up to 24 dual-mirror telescopes (MST’s)

**High energies**
10 km² area at few TeV
4 to 6 m diameter
up to 70 telescopes (SST’s)
Full Sky Coverage

North + South

>60° zenith
45°-60°
30°-45°

South

North
Major improvement over a wide energy range
Flux Sensitivity (Crab units)

For detection in each 0.2-decade energy bin

Array I 50 hours 5 sigma

rate (=area) limited

background and systematics limited

background limited

LST

MST

SST

all

Differential sensitivity (C.U.)

Energy (TeV)
Galactic Discovery Reach

Current Galactic VHE sources (with distance estimates)

Survey speed: x300 faster than HESS
Sensitivity below thermal relic in TeV mass range
- critical complementarity to direct detectors and LHC
Region where data is critically needed

$A_{\text{coll}} \sim 10^7 \text{ m}^2 \text{ above } 10 \text{ TeV}$

Crucial for:
High-energy spectra, discovery of Pevatrons $\rightarrow$ Origin of CRs
Angular resolution critical for source morphology and identification.

Galactic-Center region
Transient Capability (< 100 GeV)

Hinton & Funk
arXiv:1205.0832

S. Inoue et al.,
arXiv:1301.3014

Huge potential for short-timescale phenomena (GRB’s, AGN, Micro-quasars, etc.)
CTA Implementation & Status
Southern & Northern Sites

**South site**
- 4 large 23m telescopes: LST
- 25 medium 12m telescopes: MST
- 24 medium 10m telescopes: SCT (US)
- 70 small 4m telescopes: SST

**North site**
- 4 large LST
- 15 medium MST

Distance between sites:
- 3 km
- 800 m
# Telescope Specifications

<table>
<thead>
<tr>
<th></th>
<th>LST “large”</th>
<th>MST “medium”</th>
<th>SCT “medium 2-M”</th>
<th>SST “small”</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Number</strong></td>
<td>4 (S) 4 (N)</td>
<td>25 (S) 15 (N)</td>
<td>24 (S)</td>
<td>70 (S)</td>
</tr>
<tr>
<td><strong>Energy range</strong></td>
<td>20 GeV to 1 TeV</td>
<td>200 GeV to 10 TeV</td>
<td>200 GeV to 10 TeV</td>
<td>&gt; few TeV</td>
</tr>
<tr>
<td><strong>Effective mirror area</strong></td>
<td>&gt; 330 m²</td>
<td>&gt; 90 m²</td>
<td>&gt; 40 m²</td>
<td>&gt; 5 m²</td>
</tr>
<tr>
<td><strong>Field of view</strong></td>
<td>&gt; 4.4°</td>
<td>&gt; 7°</td>
<td>&gt; 7°</td>
<td>&gt; 8°</td>
</tr>
<tr>
<td><strong>Pixel size ~PSF θ₈₀</strong></td>
<td>&lt; 0.11°</td>
<td>&lt; 0.18°</td>
<td>&lt; 0.075°</td>
<td>&lt; 0.25°</td>
</tr>
<tr>
<td><strong>Positioning time</strong></td>
<td>50 s, 20 s goal</td>
<td>90 s, 60 s goal</td>
<td>90 s, 60 s goal</td>
<td>90 s, 60 s goal</td>
</tr>
<tr>
<td><strong>Target capital cost</strong></td>
<td>7.4 M€</td>
<td>1.6 M€</td>
<td>2.0 M€</td>
<td>420 k€</td>
</tr>
</tbody>
</table>
Large Telescope (LST)

23 m diameter
389 m² dish area
28 m focal length
1.5 m mirror facets

4.5° field of view
0.1° pixels
Camera ø over 2 m

Carbon-fiber structure for 20 s positioning

Active mirror control

4 LSTs on South site
4 LSTs on North site
Prototype = 1st telescope
LST Full Prototype

Elevation drive prototype

Mirror prototype (cold-slump, Sanko)

Area = 1.96 m²
Mass = 47 kg

Prototype Camera design
Medium Telescope (MST)

- 100 m² dish area
- 16 m focal length
- 1.2 m mirror facets
- ~2000 x 0.18° pixels
- 8° field of view

Prototype at DESY (Berlin)

25 MSTs on South site
15 MSTs on North site
MST Cameras and Mirror Control

Prototype automatic mirror control (AMC)

Flash-ADC + digital trigger + rack electronics (“FlashCAM”)

Capacitor pipeline + analog trigger + fully-contained “drawers” (“NectarCAM”)

Nectar-board prototype
Small Telescope 1-mirror (SST-1M)

SST-1M Prototype Inauguration, 2 June 2014 (Krakow)
Silicon-PMT Camera
Two-Mirror Telescopes

Schwarzschild-Couder (SC) Design

Vassiliev, Fegan, Brousseau

- Reduced plate scale
- Reduced PSF
- Uniform PSF across f.o.v.

- Cost-effective small telescopes with compact sensors (SST-2M)
- Higher-performance medium telescopes with small pixels (MST-SCT)
Small Telescope 2-mirror (SST-2M)

SST-2M –ASTRI PROTOTYPE INAUGURATION, 24 SEPT 2014 (SERRA LA NAVE, SICILY)

SST-2M-GCT (GATE-CHEC TELESCOPE)

Both 2-Mirror SST Designs use compact, Silicon-PM Cameras
SST-2M -ASTRI Focal Plane

Each PDM works independently from the others

ASTRI Focal Plane

4×4 Units → 1 PDM
56×56mm
(64 channels)

37 PDMs → Focal Plane
560×560mm
(1984 channels)

S11828-3344M1
the ‘Unit’

dead area

Logical pixel
6.2×6.2mm
≡ 0.17°
(4 channels)
SST-2M-GCT Camera + Module

- Lid
- Pointing LEDs
- 32 Photosensor modules
- Enclosure
- LED Flasher Units
- Enclosure
- ~0.4 m
- ~45 kg
- ~450 W
- Liquid cooling
- Photosensor module
Medium Telescope 2-mirror (SCT)

- 9.7 m primary
- 5.4 m secondary
- 5.6 m focal length, f/0.58
- 40 m² eff. coll. area
- PSF better than 4.5′ across 8° fov

- 8° field of view
- 11328 x 0.07° SiPMT pixels
- Target readout ASIC

Extend South array by adding 24 SCTs

- Increased γ-ray collection area
- Improved γ-ray angular resolution
SCT Prototype Development

Prototype panels for primary mirror (M1)

Camera design, backplane and elements

Individual (64-chan) Camera module

Target-7 ASIC
Prototype location at Whipple basecamp (near VERITAS, Arizona USA)

Soon: Positioner installed
Summer: Camera delivered
Fall: Start of commissioning

Positioner from DESY (Same as MST)
Site Selection

Two sites to cover full sky at 20°-35° N, S

North: Decision for which site to negotiate aimed for Spring 2015 (Arizona, Canary Islands, San Pedro Martir)

South: negotiations started with ESO/Chile and Namibia; Conclusion likely not before summer 2015. Argentinian site kept as 3rd option.
Site Selection

Two sites to cover full sky at 20°-35° N, S

USA – Meteor Crater
Spain – La Palma
Mexico – San Pedro Martir
Namibia – Aar
Argentina – Leoncito
Chile – Armazones
Steps Towards Approval

Science Performance and Preliminary Requirement Review

Preliminary Technical Design Report / Preliminary Design Review

Technical Design Report / Critical Design Review

Founding Agreement


EC-supported Preparatory Phase, followed by CTA GbmH, for legal support

CDR scheduled for June 2015 by Science and Technical Advisory Committee (STAC) – Chair. R. Blandford

After approval, assume 5-year construction phase
Open Access, Public Data

First Time in this field

Delivery to user: FITS data files, FERMI-like analysis tools

All CTA data and associated tools will be fully open after a proprietary period
Key Science Projects (KSPs)

The KSPs are:

- aimed to ensure that some of the key science issues for CTA are addressed in a coherent fashion, with well-defined strategy
- typically hard to carry out within a Guest Observer program.
- planned, proposed, carried out by CTA Consortium under guaranteed time
- conceived to provide legacy data sets for use by the entire community

The KSPs will evolve over time!
KSP Scheduling

Time sharing

All CTA data will be fully open after a proprietary period.
Galactic Plane Survey (GPS)

Entire plane surveyed to < 3.8 mCrab
Galactic Center

Very deep exposure around SGR A*, covering central source, DM halo, radio lobes.

GPS pointings

Deep exposure in $10^\circ$ by $10^\circ$ region, to edge of Gal. bulge, Covering radio spurs, base of Fermi bubbles, Kepler SNR.
Extragalactic Survey

Survey ~1/4 of sky (overlapping with GPS)
Caveat: Observatory timelines are very uncertain; this represents a notional picture based on available information.
HAWC & CTA

Wide FOV
100% duty cycle
N hemisphere
Moderate resolution

Moderate FOV
15% duty cycle
N & S Hemispheres
Excellent resolution

Complementary Capabilities!

We can envision many ways to collaborate effectively
Summary

- **We’ve learned a lot from previous/present experiments**

  Fruitful science & power of the atmospheric Cherenkov technique
  → new, much more powerful Observatory using IACTs

- **Cherenkov Telescope Array (CTA)**

  Science drivers → Design → Performance → Science Capabilities
  Design of the Arrays, Status of Prototype construction
  CTA Consortium and the Key Science Projects
  Open Observatory
  2015: Update on site and critical design review

- **HAWC: an important VHE instrument → great science**

  In few years, CTA will provide powerful data to complement HAWC
  We look forward to close cooperation between HAWC & CTA
Congratulations HAWC!

On behalf of the CTA Consortium, congratulations to the HAWC collaboration on reaching this important milestone!
CTA South Array
CTA Galactic Plane Survey

Simulation for $|l| < 60^\circ$
## CTA Key Science Projects (KSPs)

Ten KSPs to be proposed

<table>
<thead>
<tr>
<th>Theme</th>
<th>Question</th>
<th>Dark Matter Programme</th>
<th>Galactic Centre</th>
<th>Galaxy Clusters</th>
<th>LMC Survey</th>
<th>Active Galaxies</th>
<th>Star-forming Systems</th>
<th>Galactic Plane Survey</th>
<th>Extreme Accelerators</th>
<th>Transients</th>
<th>Extragalactic Survey</th>
<th>Cygnus Region</th>
</tr>
</thead>
<tbody>
<tr>
<td>Understanding the Origin and Role of Relativistic Cosmic Particles</td>
<td>1.1 What are the sites of high-energy particle acceleration in the universe?</td>
<td>✓</td>
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<td>1.2 What are the mechanisms for cosmic particle acceleration?</td>
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<tr>
<td></td>
<td>1.3 What role do accelerated particles play in feedback on star formation and galaxy evolution?</td>
<td>✓</td>
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<td>2.1 What physical processes are at work close to neutron stars and black holes?</td>
<td>✓</td>
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<td>2.2 What are the characteristics of relativistic jets, winds and explosions?</td>
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<td>2.3 How intense are radiation fields and magnetic fields in cosmic voids, and how do these evolve over cosmic time?</td>
<td>✓</td>
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<tr>
<td>Exploring Frontiers in Physics</td>
<td>3.1 What is the nature of Dark Matter? How is it distributed?</td>
<td>✓</td>
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<td></td>
<td>3.2 Are there quantum gravitational effects on photon propagation?</td>
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<td>3.3 Do Axion-like particles exist?</td>
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</table>
Science Verification, Early Science

Best effort
Priority on commissioning

“Guaranteed” minimum performance
Observatory-mode operation

Deployment status

Science Verification
Early science
KSPs

Open time

Time

trial open time?

This is a notional view!
Essentially all needed observations completed in the two years.
Scientific Motivation

Broad motivations for VHE $\gamma$-ray Astronomy:

**PHYSICS Motivations**
- Origin of Cosmic Rays - energy balance of Galaxy
- Physics of compact objects
- Physics Frontiers (e.g. DM)

**ASTRONOMICAL Motivations**
- New observational window into non-thermal Universe
- High energy particle (e,p) accel. - shocks, winds, jets, etc.

Multiwavelength/Multi-Messenger Observations

Radio  X-rays  HE $\gamma$-rays  VHE neutrinos  Grav. waves
VHE Multi-Messenger Astrophysics

- **Black Hole**
- **Jet**
- **EeV Cosmic Rays**
- **PeV Neutrinos**
- **GeV/TeV γ-rays**
- **Active Galactic Nucleus (AGN)**

Diagram showing connections between different astrophysical phenomena.
The High Energy Milky Way

H.E.S.S. (TeV)
Extended sources, size typically few 0.1°
  few 10 pc

Fermi-LAT (GeV)

Courtesy of W. Hofmann
The Many Faces of TeV Particle Acceleration

- **Pulsars**
  - NS dynamo
  - Jets powered by accretion or unipolar induction. UHECR's?

- **AGN**
  - Gamma-Ray Bursts
  - Star collapse \(\rightarrow\) relativistic jets

- **Star Forming Regions**
  - SNRs, cosmic rays, molecular clouds.

- **Supernova Remnants**
  - Fermi Acceleration
  - Accretion jets or stellar winds

- **Unidentifieds**

- **Binary Systems**
WIMP DM Complementary Approaches

WIMP annihilation
In the cosmos

Indirect Detection

WIMP-Nucleon
Elastic scattering

Direct Detection

Heavy particle prod.
MET + jets
Weak pair prod.
MET + monojet

LHC Production
WIMP Indirect Detection

WIMP Annihilation

- Gamma rays
- Neutrinos
- Anti-matter

Particle Physics
(Uncertainty from \( m_\chi \), decay modes, etc.)

\( \gamma \gamma \ |
\( Z\gamma \ |
\( \gamma \) (cont.)

- GeV
  - Fermi, AGILE
    (Satellite)
- TeV
  - HESS, MAGIC
    VERITAS
    (Atm. Cherenkov)

\( \nu \) from Sun

- GeV-TeV
  - IceCube, Antares
    Super-K
    (Ice/Water Cherenkov)

\( e^+ , \bar p , \bar d \) in CR

- GeV-TeV
  - PAMELA, Fermi, AMS
    (Satellite)
WIMP Indirect Detection: $\gamma$-rays

Gamma rays from DM annihilation:

$$
\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma, \phi, \theta) = \frac{1}{4\pi} \frac{< \sigma_{\text{ann}} v >}{2m_{\text{WIMP}}^2} \sum_f \frac{dN_{\gamma f}}{dE_\gamma} B_f \times \int d\Omega' \int_{\text{los}} \rho^2(r(l, \phi')) dl(r, \phi')
$$

DM distribution

Line-of-sight Integral (Uncertainty from unknown DM profile)

Where to look:

- The Galactic Center
  - Brightest spot in the sky
  - Considerable astrophysical backgrounds
- The Galactic Halo
  - High statistics
  - Requires detailed model of galactic backgrounds
- Isotropic Background
  - High statistics
  - Potentially difficult to identify
- Dwarf Galaxies
  - Less signal
  - Low backgrounds

What to look for:

D. Hooper, Aspen 2013