Science with the Cherenkov Telescope Array (CTA)

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on behalf of the CTA Consortium

www.cta-observatory.org

Imaging the Extreme Universe
Solid-state Cameras for Astroparticle Physics
KICP, University of Chicago
May 9, 2013
Science with the Cherenkov Telescope Array (CTA)

CTA design goals:
- 10-fold increase in sensitivity over current VHE $\gamma$-ray instruments
- energy range of $\sim 30$ GeV - $100$ TeV
- large ($\sim 8^\circ$) field of view for surveys
- improved angular and energy resolution
- operate as an open observatory

CTA science goals:
- understanding where and how the bulk of CR particles are accelerated
- what makes black holes of all sizes such efficient particle accelerators
- the nature of dark matter
- $\gamma$-ray probe for the fundamental laws of physics

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B.S. Acharya et al. 2013, APh, 43, 3
Imaging Atmospheric Cherenkov Technique

Y-rays interact with the atmosphere at a height of 15-30 km above ground -> creates an air shower of cascading interactions over 10 km in length

image the air shower with multiple telescopes to determine the direction and energy of the Y-ray

ground-based detection
- energy range ~30 GeV - 100 TeV
- large effective area of ~10^5 m^2
Currently Operating VHE $\gamma$-ray Instruments

**MAGIC**: located in La Palma, Spain
- since 2004: single 17m telescope
- since 2009: system of two 17m telescopes

**HESS**: located in Khomas Highlands, Namibia
- since 2002: four 12m telescopes
- since 2012: added 32m by 24m telescope

**VERITAS**: located in Mt Hopkins, Arizona
- since 2007: four 12m telescope
- since 2012: upgraded PMTs in all telescopes
Maximizing the Sensitivity, Resolution, and Energy Range

telescopes (100 m spacing)

air shower
Cherenkov light-pool (150 m radius)

sweet spot for reconstruction of shower

large array of telescopes:
more recorded images of air shower

light pool from simulations

potential array configuration
(from simulation study)

telescope size: large, medium, small
Introduction

- Development of camera for Schwartzschild-Couder MST prototype (see Vladimir Vassiliev's talk Thursday)
- Work now funded by NSF MRI
- Three year time-scale to complete prototype at VERITAS site

Fig. 5. Three possible designs for SSTs of about 4 m mirror diameter, with 8–10° FoV and 1300–2000 pixels of 0.2–0.3°. Top and bottom right: Schwarzschild–Couder dual-mirror optics. Bottom left: Traditional Davies–Cotton design with f/D = 1.4 and a large camera.

FoV also requires technically challenging telescope optics. With the current single-mirror optics and f/D ratios in the range up to 1.2, an acceptable point spread function is obtained out to radii of 4–5°. Larger FoVs with single-mirror telescopes require increased f/D ratios, in approaching 2 for a 10° FoV, which are mechanically difficult to realise since a large and heavy focus box needs to be supported at a long distance from the mirror. Also, the single-mirror optics solutions, which provide the best imaging, use the Davies–Cotton design, which in turn result in a time dispersion of the Cherenkov photons that seriously affects the trigger performance, once the mirror diameters exceed 15 m (for the typical f/D ratios). An alternative solution is the use of dual-mirror optics. With non-spherical primary and secondary mirrors, good imaging over fields of up to 10° diameter can be achieved, but the disadvantages are the increased cost and complexity, significant shadowing of the primary mirror by the secondary, and complex alignment issues for faceted primary and secondary mirrors. Large incidence angles of photons onto the camera, which is common in dual-mirror optics, affects the photo detection efficiency and may require baffling of stray light.

Therefore, the choice of the FoV requires that science gains, cost and increased complexity be carefully balanced. When searching for unknown source types which are not associated with non-thermal processes in other, well-surveyed wavelength domains, a large FoV helps, as several sources may appear in one pointing. This increases the effective observation time per source by a corresponding factor compared to an instrument that can look only at one source at a time. An instrument with CTA-like sensitivity is expected to detect of the order of 1000 sources. In the Galactic plane, one would always find multiple sources in a FoV. In extragalactic space, the average angular distance between (an estimated 500) sources would be about 10°, implying that even for the maximum conceivable FoVs the gain is modest, but not negligible. Even in the Galactic plane, a very large field of view will not be the most cost effective solution, since the gain in terms of the number of sources viewed simultaneously scales essentially linearly with the diameter of the field of view, given that sources are likely to cluster within a fraction of a degree from the Galactic plane, whereas camera costs scale with the diameter squared. A rough estimate based on typical mirror costs and per-channel pixel and readout costs...
Schwarzschild-Couder Telescopes

by design provides large field of view (8-9°) and compact camera (SiPM detectors) >11,000 pixels (0.07°) and good QE

primary mirror: 9.7 m diameter
secondary mirror: 5.4 m diameter

Full Optical Support Structure
Full primary mirror; M1: 16+32
Full positioning system
Camera: 1,600 of 11,328 channels

SC prototype with reduced secondary mirror and camera -> begin construction in 2014

propose: 36 SC telescopes at Southern CTA site

location of prototype SC telescope:
VERITAS site at Mt Hopkins, AZ
Medium-Size Telescope (MST-DC) Prototype near Berlin
Sensitivity of CTA

order of magnitude improvement in sensitivity over HESS and VERITAS

S. Funk et al. 2013, APh, 43, 348
Sensitivity of CTA

simulated array performance

Fermi LAT (3 yr)

~2-3x improvement in core energy range from US contribution

Angular and Energy Resolution of CTA

**Angular Resolution**
- 1-2 arcmin
- Localization of point-sources: < 5 arcsec

**Energy Resolution**
- Systematic uncertainty < 10-15%

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Figure 2:
Left: Angular resolution for Fermi-LAT [29] and CTA [30]. H.E.S.S. [31] and HAWC [32] are shown as examples for a current-generation IACT and for a next-generation water Cherenkov detector. Also shown is the limiting angular resolution that could be achieved if all Cherenkov photons emitted by the particle shower could be detected [33]. The CTA curve has not been optimized for angular resolution and enhanced analysis techniques are expected to improve this curve.

Right: Energy resolution for Fermi-LAT and CTA. Shown is the 68% containment radius around the mean of the reconstructed energy. It is evident that the energy resolution of Fermi-LAT in the overlapping energy range is significantly better than the CTA resolution.

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S. Funk et al. 2013, APh, 43, 348
CTA Site Selection

Northern sites under investigation:
- Meteor Crater, Arizona, USA
- San Pedro Martir, Mexico
- Tenerife, Spain

Souther sites under investigation:
- Aar, Namibia
- San Antonio, Argentina
- near Paranal, Chile

Site decision by early 2014

site evaluation (scientific)
- annual observing time (clear skies)
- best instrument sensitivity
  (dark, steady, high-transmission skies)
- atmosscopes for weather monitoring
- remote (satellite) data comparisons

site evaluation (costs and risks)
- construction costs
- operations costs
- facility / personal risks
CTA Projected Timeline

SCT roadmap

- 2005
- 2009
- 2012
- 2013
- 2014
- 2015
- 2016
- 2017
- 2018

Ideas of large IACT arrays originated

SCT and AGIS ideas formulated

SCT MRI funded

pSCT design Completed

pSCT Verified and Commissioned

First projected opportunity for initial CTA Extension construction funds in the US (NSF/DOE)

US CTA construction proposal to be submitted

Hybrid MST-SCT installation

Projected CTA construction

P5 Report “The Cosmic Frontier” 2008

HEPAP PA SAG Report 2009

pSCT constructed

AADS 2010 Report “New Worlds, New Horizons in Astronomy and Astrophysics” 2010

Science, August 2010
<table>
<thead>
<tr>
<th>CTA Science Goals</th>
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<tr>
<td>1. produce the deepest surveys of the sky at Y-ray energies with unprecedented angular and energy resolution</td>
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<td>2. test SNR-origin of cosmic-rays; lepto-hadronic production &amp; propagation</td>
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<td>3. assess cosmic-ray population in galaxies/starbursts and clusters</td>
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<td>4. perform the most sensitive Y-ray observations on short timescales</td>
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<td>5. expand the population of Y-ray emitting AGN (in flaring and steady-states) to study unification schemes, evolution, and gamma-ray origin</td>
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<td>6. strong constraints on the EBL and IGMF</td>
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<td>7. sensitivity to probe canonical WIMP DM models</td>
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<td>8. precision tests of Lorenz Invariance Violation</td>
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CTA Science: (1) Surveys

- highly sensitive surveys provides strong discovery potential
- aim for uniform sensitivity of ~3 mCrab along Galactic Plane
- complementary extragalactic coverage to HAWC

Simulation of 500 Pulsar Wind Nebula in the CTA Galactic Survey

Dubus et al. 2013, APh, 43, 317
Current Galactic VHE sources (with distance estimates)

Estimated fraction of PWN detected by CTA as a function of distance from Earth assuming 20 hr, faint sources (2% Crab flux):
- predict a total of 300 - 600 PWN in our Galaxy

E. de Ona-Wilhelmi et al. 2013, APh, 43, 287
estimated fraction of PWN detected by CTA as a function of distance from Earth assuming 20 hr, faint sources (2% Crab flux)
- predict a total of 300 - 600 PWN in our Galaxy
IC 443: CTA simulated spectra (blue points)

Morphology studies:
simulated CTA image of RX J1713.7-3946 from 50 hr data
(bottom left) RX J1713 actual distance (1 kpc)
(bottom left) RX J1713 at a distance of 4 kpc

Acero et al. 2013, APh, 43, 276
CTA Science: (3) Cosmic Rays in Star-forming Galaxies

- CTA sensitivity to star-forming galaxies provides insight to cosmic ray acceleration and interaction efficiencies
- test gamma-ray luminosity scaling with star formation rate

![Image of Fermi LAT luminosity vs star-formation rate](image-url)

**NGC 253**

<table>
<thead>
<tr>
<th>Energy (GeV)</th>
<th>$E^2dN/dE$ (erg cm$^{-2}$ s$^{-1}$)</th>
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<tbody>
<tr>
<td>$10^{-2}$</td>
<td>$10^{-13}$</td>
</tr>
<tr>
<td>$1$</td>
<td>$10^{-12}$</td>
</tr>
<tr>
<td>$10^{2}$</td>
<td>$10^{-13}$</td>
</tr>
<tr>
<td>$10^4$</td>
<td>$10^{-14}$</td>
</tr>
<tr>
<td>$10^6$</td>
<td>$10^{-15}$</td>
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K. Bechtol et al. 2012, 4th Fermi Symposium
wide range of exciting science topics with γ-ray flares:

- CTA offers detailed VHE γ-ray study of GRBs
- constraints on black hole and jet physics in AGN
- formation of relativistic outflows in binaries
- precision tests of Lorentz Invariance from flares

S. Funk et al. 2013, APh, 43, 348

Acero et al. 2013, APh, 43, 276

CTA simulation of GRB 090902B based on an extrapolation of the Fermi LAT spectrum at 50 sec after the trigger
CTA Science: (5) AGN population and flaring

- greatly expand the catalog of VHE γ-ray AGN
- study missing link between supermassive black hole environment and the formation of relativistic jets

AGN detectable by CTA in 50 hr (extrapolated from 2FGL sources)

173 sources total

Simulated CTA lightcurve of PKS 2155-304 (flux >50 GeV in 7.5 sec bins)

H. Sol et al. 2013, APh, 43, 215
measurements and limits on the EBL density

- CTA spectra of AGN will place strong limits on the EBL density, which is difficult to measure directly
- evolution of the EBL density offers new insights into structure formation and galaxy evolution
CTA Science: (6) Probe to Intergalactic Magnetic Fields (IGMFs)

- CTA offers a powerful probe to the predicted weak IGMF
- detection of extended $\gamma$-ray emission or a pair halo could provide highly valuable information on the IGMF, exploring the potential origin of magnetic fields in galaxies

primary and secondary $\gamma$-rays from a distance of 120 Mpc
(top) IGMF strength $\sim 10^{14}$ G
(bot) IGMF strength $\sim 10^{15}$ G

H. Sol et al. 2013, APh, 43, 215
CTA Science: (7) Search Indirect Detection of Dark Matter

- CTA will have sufficient sensitivity to probe an annihilation cross-section of $\sim 3 \times 10^{-26}$ cm$^3$ s$^{-1}$ for the Galactic Center Halo in 100 hr for WIMP masses above 300 GeV
- good energy resolution to search for DM spectral features

![Cold Dark Matter by Cornelia Parker](image)

Minimum boost factor for 5σ detection with CTA in 100 hr for dwarf galaxies

M. Doro et al. 2013, APh, 43, 189
CTA observations of distant γ-ray sources (GRB and AGN) offers a far more sensitive probe to Lorentz violation than accelerators and astrophysical neutrino measurements.

delay in arrival time of γ-ray per energy vs redshift
- line shows model where the velocity of light is reduced by an amount linear in photon energy

J. Ellis & N. Mavromatos 2013, APh, 43, 50
M. Doro et al. 2013, APh, 43, 189
Conclusions

Legacy of CTA:
physics impact of a high-sensitivity VHE γ-ray observatory will cover a wide range of modern astrophysics topics

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