The pSCT: an innovative, next-generation ground-based gamma-ray observatory

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Summer Colloquium Series - 2020
Outline

- VHE γ-ray astronomy
  - How does the sky look like in VHE γ-rays?
  - Emission mechanisms
  - γ-ray sources
  - Satellite vs. ground-based experiments

- Imaging Atmospheric Cherenkov Telescopes
  - Principle of operation
  - Current and next-generation observatories

- The prototype Schwarzschild-Couder Telescope
  - Optics
  - Detectors
  - Electronics
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Beyond the eyes

A much wider instrument to play with...

Visible

https://www2.lbl.gov/MicroWorlds/ALSTool/EMSpec/EMSpec2.html

https://www.deviantart.com/vidpen/art/The-very-long-piano-56181014
The optical sky...

Integral flux above 1 TeV in units of % of the Crab nebula, the brightest VHE γ-ray source in the sky. Image taken from (H.E.S.S. Collaboration et al. 2018b)
Emission mechanisms (VHE $\gamma$-rays)

- Inverse Compton (IC) scattering:
  - Ultra-relativistic electrons scatter low-energy ambient photons to high energies $\rightarrow$ the photons gain energy at the expenses of the electrons’ kinetic energy

- $\pi^0 \rightarrow \gamma\gamma$
  - Relativistic protons and nuclei interact on ambient gas through inelastic collisions, producing both charged ($\pi^{+-}$) and neutral pions ($\pi^0$)
VHE γ-ray sources

Galactic sources

- **Pulsar Wind Nebulae (PWN)**
  - Wind of $e^+/e^-$ accelerated to relativistic energies by magnetic field of a rotating neutron star (pulsar)

- **Supernova Remnants (SNRs)**
  - Remnants of a Supernova explosion expanding into the interstellar medium (ISM) → sources of bulk (protons and heavier nuclei) of galactic Cosmic Rays (CRs)?

- **Binary systems**
  - Compact object (e.g. a NS) and a massive star companion. VHE γ-ray emission possibly from particles accelerated at the shock between the wind of the massive star and the one of a pulsar

Extragalactic sources

- **Active Galactic Nuclei (AGN)**
  - A SMBH at the center of a galaxy accretes material from the galaxy dense central region; narrow beams of energetic particles are produced and ejected outward in opposite directions away from the disk

- **Gamma-Ray Bursts (GRBs)**
  - Short and sudden e.m. signals in the gamma-ray band which, for a few blinding seconds, become the brightest objects in the Universe (see Dr. E. Bissaldi’s talk from this series)
VHE γ-rays from Eta Car

Animation: DESY, Science Communication Lab; Sound by Alva Noto
https://www.youtube.com/watch?time_continue=187&v=uUFJXjIhUkQ&feature=emb_logo

Astronomy & Astrophysics, 2020; DOI: 10.1051/0004-6361/201936761
Satellite vs. ground-based experiments

Transparency of the atmosphere for radiation of different wavelengths. The solid line shows the height above sea-level at which Earth’s atmosphere is 50% transparent to incoming electromagnetic radiation, for radiation of different wavelengths. Figure taken from Longair (2011)
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Imaging Atmospheric Cherenkov Telescopes

Schematic view of an e.m. shower. Figure taken from Matthews (2005)

- A γ-ray photon (E₀) enters the atmosphere and generates an electromagnetic shower
- vₑ⁺(e⁻) > c/n → Cherenkov photons are emitted
- A telescope placed in the light pool can image the shower by means of a camera (usually photomultiplier-based) reconstructing energy and direction

Imaging of a γ-ray initiated e.m. shower by a telescope. Image taken from Völk and Bernlöhr (2009)
A picture of an e.m. shower - 1

- Cherenkov light beamed around the direction of incident primary particle → illuminates on the ground an area of ~250m in diameter (Cherenkov light pool)
- Light collected by a large dish and focused on a PMT camera
- The image from a γ-ray-induced shower can be parametrized with an ellipse (Hillas, 1985) → Hillas parameters: width, length, distance of image axis to the camera center, orientation angle, size of the image (related to shower energy)

https://www.mpi-hd.mpg.de/hfm/HESS/pages/about/telescopes/
A picture of an e.m. shower - 2

• Multiple telescopes → stereoscopic reconstruction of the shower: improved angular and energy resolution

https://www.mpi-hd.mpg.de/hfm/HESS/pages/about/telescopes/
Background contamination

CR-induced hadronic showers can be distinguished by the different shape of their image in the camera (though some of these events can be still mis-recognized as $\gamma$)

Difference between the images of gamma-induced and hadron-induced showers in the camera (from K. Bernlöhr)

- CR-induced hadronic showers can be distinguished by the different shape of their image in the camera (though some of these events can be still mis-recognized as $\gamma$)
Current-generation IACTs
Next-generation IACT

Artistic impression of the CTA South, Credit Gabriel Pérez Diaz, IAC / Marc-André Besel CTAO
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A dual-mirror system

The prototype Schwarzschild-Couder Telescope (pSCT) at the Fred Lawrence Whipple Observatory in Amado, Arizona. Credit: Amy C. Oliver, Center for Astrophysics | Harvard & Smithsonian
Big eyes and a sharper view

- Superior optical angular resolution over a wide (~8°) field of view
- By focusing the light on a smaller surface, enables the use of state-of-the-art sensors (SiPMs) and electronics
- Better sensitivity and reduced observation time
Focal plane structure

Full camera = 9 sub-fields
177 modules
11,328 image pixels

1 sub-field = 25 modules

2.68° FOV

Module of 64 image pixels

4 image pixels = 1 trigger pixel

The detectors: Silicon Photomultipliers

SiPMs: array of reverse-biased Single Photon avalanche Diodes (SPADs) connected in parallel, each with integrated quenching resistor

SiPM size: from 1x1mm$^2$ to 10x10mm$^2$

SPAD size: from 5µm to 40µm (typical)

http://advansid.com/resources/the-silicon-photomultiplier
Main SiPM characteristics

**High PDE**

Gola et. al. [https://www.mdpi.com/1424-8220/19/2/308](https://www.mdpi.com/1424-8220/19/2/308)

**Single p.e. resolution**

Bonardi et. al 2014

- Ruggedness
- Insensitivity to magnetic fields
- ...

[https://webstockreview.net/explore/thumb-clipart-hand/](https://webstockreview.net/explore/thumb-clipart-hand/)
The pSCT FEE electronics

Design and Performance of the Prototype Schwarzschild-Couder Telescope Camera – in preparation

M. Capasso - SCS 2020
Announcement

CTA Prototype Telescope, the Schwarzschild-Couder Telescope, Detects Crab Nebula


CTA is a partnership between the Netherlands (NWO SRON), Germany (DLR), Switzerland (ETH Zurich), Italy (INAF), France (IPNO), Spain (INFNEA), Sweden (MAX IV), the United Kingdom (STFC), and the United States (LanL, SLAC). Its development is funded by these governments. CTA will require an international collaboration between universities, institutes, foundations and governments.
Looking at the Crab

Animation showing 18 gamma-ray events from the Crab Nebula detected with the pSCT telescope. Credit: CTA/SCT consortium

Sky map recorded with the pSCT over a region centered on the Crab Nebula, detection of the Crab Nebula marked at center. Credit: CTA/SCT consortium

Histogram showing the detection of gamma-ray events from the Crab Nebula, with NOFF representing background and NON representing a combination of signal and background. Credit: CTA/SCT consortium
Upgrading the prototype

Preamplified and shaped signal from SMART chip (not to scale)

SiPM signal (not to scale)

Figure 5. (top) Sketch of the upgraded camera FEE module, the Auxiliary and Primary boards are shown on top and bottom, respectively. Both boards have been logically divided into an analog and digital/power sections. (bottom) Picture of the prototype FEE module currently under test.

R. Paoletti: SPIE 2019
Summary and outlook

- VHE $\gamma$-ray astronomy is a powerful tool to explore the energetic Universe
- In the last 20+ years, IACT technology has continuously improved, opening the window to the farthest accessible $\gamma$-ray band (around 1 TeV and beyond)
- The next-generation observatory (CTA) is under construction
- Within CTA, the pSCT represents a high-potential, first-of-its-kind IACT
  - Technology validation: Crab detection
  - Towards the upgrade: lower-noise electronics + fully populated (11k+ pixels) camera
Stay tuned!

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