Unraveling the very-high-energy Universe with ground-based Cherenkov telescopes

Massimo Capasso
Barnard College, Columbia University
(capasso@nevis.columbia.edu)

2021 Nevis Labs REU Lectures

07/06/2021
Outline

- γ-rays and VHE γ-ray astronomy
  - What are γ-rays?
  - Sources of γ-rays
  - How does the sky look like in VHE γ-rays?
  - Satellite vs. ground-based experiments

- Imaging Atmospheric Cherenkov Telescopes
  - Principle of operation
  - Past, current and next-generation observatories
    - The prototype Schwarzschild-Couder Telescope (pSCT)

- Live tour!!!
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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
Sources of γ-rays

But there is more...

https://en.wikipedia.org/wiki/Gamma_ray
https://www.marvel.com/comics/issue/8906/incredible_hulk_1962_1
γ-rays are everywhere!

Our Solar «backyard»

https://svs.gsfc.nasa.gov/11000

Our Galactic «backyard»

https://commons.wikimedia.org/wiki/File:Cassiopeia_A_A_Spitzer_Crop.jpg

Outside our Galaxy

https://en.wikipedia.org/wiki/Active_galactic_nucleus#/media/File:M87_jet.jpg
γ-rays emission mechanisms

Accelerated particles + matter

Accelerated particles + radiation field

Accelerated particles + magnetic field

Interstellar medium (ISM)

π⁰ decay

Bremsstrahlung

Inverse Compton scattering

Synchrotron emission

https://www.schoolphysics.co.uk
Fingerprinting the particle population

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Broadband spectral energy distribution (SED) model of Tycho’s SNR. Image taken from Giordano et al. (2012).

https://www.thecomicstrips.com/comic-strip/Frank+and+Ernest/2010-04-02/45896
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)
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
- νₑ⁺(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 closer look at the components of an IACT

Detectors

Camera

Optics
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

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 γ)
IACT pioneers: the Whipple 10 m γ-ray telescope at FLWO

https://veritas.sao.arizona.edu/whipple
Current-generation IACTs

https://magic.mpp.mpg.de


http://veritas.sao.arizona.edu
Next-generation IACT

Artistic impression of the CTA South, Credit Gabriel Pérez Diaz, IAC / Marc-André Besel CTAO
Where is CTA?
Why CTA?

- Wider energy range
- Better sensitivity
- Better angular resolution
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

Schematic of Schwarzschild-Couder two-mirror optical system [link to PDF]


Primary
\[ D_p, F_p = \frac{1}{\alpha q} F \]

Focus
\[ D_f, F_f \]

Secondary
\[ D_s, F_s = -\frac{1-\alpha}{1-\alpha q} F \]
Pop quiz!!!

When did Karl Schwarzschild published his paper?

a) 1905
b) 1965
c) 1990
Pop quiz!!!

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Big eyes and a sharper view

- Superior optical angular resolution over a wide (~8°) field of view (the largest IACT FOV is currently less than 5°)
- By focusing the light on a smaller surface, enables the use of state-of-the-art sensors (Silicon-photomultipliers, SiPMs) and electronics
- Better sensitivity and reduced observation time
SiPMs: array of reverse-biased Single Photon avalanche Diodes (SPADs) connected in parallel

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

SPAD size: from 5µm to 40µm (typical)
Announcement

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


Media Links:
- pSCT (https://www.flickr.com/photos/cta_observatory/494732361/)
- pSCT Inauguration (https://www.flickr.com/photos/cta_observatory/494732934/)
- Event Animation (https://www.cfa.harvard.edu/wp-content/uploads/2020/05/eventl02_optimized.gif)
- Sky Map (https://www.flickr.com/photos/cta_observatory/4944201011/)
- Histogram (https://www.flickr.com/photos/cta_observatory/4944207271/)
- Film: How CTA Works (https://youtu.be/1gYbFtGpJ5U)

Armado, AZ — On 1 June 2020, scientists from the Cherenkov Telescope Array (CTA) Consortium announced at the 236th meeting of the American Astronomical Society (AAS) that they have detected gamma rays from the Crab Nebula using a prototype telescope proposed for CTA, the prototype Schwarzschild-Couder Telescope (pSCT) (https://www.cta-observatory.org/project/technology/sct/), proving the viability of the novel telescope design for use in gamma-ray astrophysics.

“The Crab Nebula is the brightest steady source of light, or very-high-energy, gamma rays in the sky; so detecting it is an excellent way of proving the pSCT technology,” said Justin VanderBroucke, Associate Professor, University of Wisconsin. “Very-high-energy gamma rays are the highest energy photons in the universe and can unveil the physics of extreme objects including black holes and possibly dark matter.”

Detecting the Crab Nebula with the pSCT is more than just proof-positive for the telescope itself. It lays groundwork for the future of gamma-ray astrophysics. “We’ve established this new technology, which we measure gamma rays with extraordinary precision, enabling future discoveries,” said VanderBroucke.

“Gamma-ray astronomy is already at the heart of the new multi-messenger astrophysics, and the CTA technology will make it an even more important player.”

The use of secondary mirrors in gamma-ray telescopes is a leap forward in innovation for the relatively young field of very-high-energy gamma-ray astronomy, which has moved rapidly to the forefront of astrophysics. “Just over three decades ago, gamma rays were first detected in the universe, from the Crab Nebula, on the same mountain where the pCCT sits today,” said VanderBroucke. “That was a real breakthrough, opening a cosmic window with light that is a trillion times more energetic than we can see with our eyes. Today, we’re using two mirror surfaces instead of one, and state-of-the-art sensors and electronics to study these gamma rays will exquisite resolution.”

CON TECNOLOGIA MADE IN ITALY, IL PIÙ GRANDE TELESCOPIO SCHWARZSCHILD-COUDER OSSERVA LA SUA PRIMA SORGENTE DI RAGGI GAMMA

COMUNICATO CONGIUNTO INFN-NAF. Il telescopio pSCT, un prototipo di telescopio di tipo Schwarzschild-Couder dell’osservatorio di prossima generazione CTA (Cherenkov Telescope Array), ha osservato la sua prima sorgente gamma, grazie a soluzioni tecnologiche innovative sviluppate in Italia dall’INFN Istituto Nazionale di Astrofisica, e dall’INFN Istituto Nazionale di Fisica Nucleare.

Massimo Capasso
An extraordinary inter-continental effort...
...still ongoing!

- Software and data acquisition optimization for the pSCT
- Optical alignment improvement
- Camera upgrade, towards a fully populated SCT
  - 1600 pixels $\rightarrow$ 11328 pixels
    ($\sim 2.67^\circ \rightarrow \sim 8^\circ$)
  - Upgraded photosensors
  - Upgraded preamplifiers
  - Upgraded electronics

Italian postdoc carefully opening the back of the pSCT camera for technical inspection (FWLO)

Photo credit: William Hanlon
Remote observing

«locally» remote (FLWO)

«remote» remote (NY)
Barnard and Columbia Contribution

Flasher calibration units

Camera slow control

Correction

No correction

Offline telescope pointing correction

Optics

On-site work

Camera upgrade PI: Prof. Reshmi Mukherjee

Camera upgrade
Some thoughts on VHE γ-ray astronomy

- VHE γ-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 γ-ray band (around 1 TeV and beyond)
- The next-generation observatory (CTA) is under construction and will dramatically enhance IACT performance
- 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
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Science On Hudson, Nevis Labs  
LIVE from the VERITAS site at FLWO

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