The future of gamma-ray astronomy

L’avenir de l’astronomie gamma

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Observing gamma rays

- Photoelectric effect
- Compton scattering
- Pair creation

- Coded masks
- Lenses
- Compton telescopes
- Particle detectors

- Space-based
- Ground-based

Radio | μWaves | IR | UV | X-rays | Gamma rays

- 10^{-9} | 10^{-6} | 10^{-3} | 10^{0} | 10^{3} | 10^{6} | 10^{9} | 10^{12} | eV

TeVPA 2016 (12-16 September 2016)
History of gamma-ray astronomy

Number of detected sources in red

2010
INTEGRAL
Fermi
> 3000

1980
32
COMPTEL

1990
271
EGRET

1960
1
Ranger 3

MeV
GeV
TeV

TeVPA 2016 (12-16 September 2016)
Achievements

Nucleosynthesis in the Universe
- 2014: $^{56}$Co lines from SN Ia
- 2003: $^{60}$Fe lines from Galaxy
- 1994: $^{44}$Ti lines from Cas A
- 1988: $^{56}$Co lines from SN II
- 1984: $^{26}$Al line from Galaxy
- 1973: GRB, solar deexcitation lines
- 1972: $e^+e^-$ 511 keV line
- 1969: Crab pulsar
- 1962: Cosmic background
- 1958: Solar flare

Cosmic rays in the Galaxy and beyond
- 2013: Proton acceleration in SNR
- 2011: Crab nebula flares
- 2010: Fermi bubbles,
  - First radio galaxy lobe, First nova
- 2009: First millisecond pulsars,
  - First starburst galaxies
- 2009: First SNR
- 2008: Crab pulsar
- 2005: First binary
- 2004: First resolved SNR
- 2002: First unidentified TeV source
- 2001: First starburst galaxies
- 2000: First SNR

Cosmic accelerators
- 2009: First starburst galaxies
- 2008: Crab pulsar
- 2005: First binary
- 2004: First resolved SNR
- 2002: First unidentified TeV source
- 2000: First SNR
- 1992: Mkn 421
- 1989: Crab nebula

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Scientific Challenges

The nature of Dark Matter

- Indicates a major flaw in our understanding of nature
- Proposed solutions include new fundamental particles (WIMPs, axions, etc.)
- Decay products of these particles may be detectable in gamma rays
Scientific Challenges

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The origin of Cosmic Rays

- Unveiling the Galactic PeVatrons
- Impact of low-energy cosmic rays on interstellar chemistry
- Cosmic-ray propagation
- Impact of environment
Scientific Challenges

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The physics of Particle Acceleration

- What mechanisms are actually at operation in a given source?
- Insights from variability (time domain astronomy)
- Elusive source classes
Space-based projects

<table>
<thead>
<tr>
<th>Parameter</th>
<th>AdEPT</th>
<th>e-ASTROGAM</th>
<th>CALET</th>
<th>DAMPE</th>
<th>GAMMA-400</th>
<th>HARPO</th>
<th>HERD</th>
<th>PANGU</th>
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<tbody>
<tr>
<td>Context</td>
<td>R&amp;D</td>
<td>M5?</td>
<td>ISS</td>
<td>China</td>
<td>Russia</td>
<td>R&amp;D</td>
<td>China</td>
<td>ESA/CAS?</td>
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<td>Launch date</td>
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<td>2029?</td>
<td>launched</td>
<td>launched</td>
<td>~2021</td>
<td>–</td>
<td>&gt;2020</td>
<td>2021?</td>
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<td>Energy range (GeV)</td>
<td>0.005–0.2</td>
<td>0.0003–3</td>
<td>0.02–10000</td>
<td>2–10000</td>
<td>0.1–3000</td>
<td>0.003–3</td>
<td>0.1–10000</td>
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<td>Ref. energy (GeV)</td>
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<td>0.1</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>0.1</td>
<td>100</td>
<td>1</td>
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<td>30%</td>
<td>30%</td>
<td>2%</td>
<td>1.5%</td>
<td>1%</td>
<td>10%</td>
<td>1%</td>
<td>30%</td>
</tr>
<tr>
<td>$A_{\text{eff}}$ (cm$^2$)</td>
<td>500</td>
<td>1500</td>
<td>t.b.d.</td>
<td>3000</td>
<td>5000</td>
<td>2700</td>
<td>t.b.d.</td>
<td>180</td>
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<td>10</td>
<td>10</td>
<td>1000</td>
<td>100</td>
<td>100</td>
<td>1</td>
<td>10</td>
<td>t.b.d.</td>
</tr>
<tr>
<td>Field of view (sr)</td>
<td>t.b.d.</td>
<td>2.5</td>
<td>1.8</td>
<td>2.8</td>
<td>1.2</td>
<td>t.b.d.</td>
<td>t.b.d.</td>
<td>2.2</td>
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<tr>
<td>Angular resolution</td>
<td>1°</td>
<td>1.5°</td>
<td>0.1°</td>
<td>0.1°</td>
<td>0.02°</td>
<td>0.4°</td>
<td>0.1°</td>
<td>0.2°</td>
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<tr>
<td>MDP (10 mCrab)</td>
<td>10%</td>
<td>20%</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>t.b.d.</td>
<td>–</td>
<td>t.b.d.</td>
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<tr>
<td>Technology</td>
<td>TPC</td>
<td>Si + CsI</td>
<td>fib. + PbWO$_4$</td>
<td>Si + BGO</td>
<td>Si + CsI</td>
<td>TPC</td>
<td>Si + LYSO</td>
<td>Si (fib.) + B</td>
</tr>
</tbody>
</table>

- Detection sensitivities are still poor in the MeV domain
- Considerable potential exists in using modern, space-proven highly pixelised semiconductor detectors in a compact configuration with a minimum amount of passive material to detect gamma rays through Compton and pair creation interactions
- At GeV energies, succeeding to Fermi-LAT will be challenging (Fermi spacecraft weight is 4.3 tons, difficult to build a much bigger detector)
- Area of improvement is angular resolution (i.e point spread function); can be achieved by decreasing density of tracker and increasing spacing between tracker and calorimeter
- Potential to cover both aspects in a single mission
Time Projection Chambers

AdEPT

- Few MeV – GeV domain, polarimetry
- Pair conversion telescope
- Gas (Ar-based) filled TPC (few bars pressure)
- Target volume: 200 x 200 x 100 cm$^3$
- $e^-e^+$ pairs drift downwards to detector plane
- Detectors
  - Gas electron multiplier and micro-well detector (AdEPT)
  - Micro-mesh and microstrip detector (HARPO)
- Prototypes built and tested
- Stratospheric balloon flights planned
- AdEPT proposed as MIDEX in U.S.

HARPO

- The demonstrator
  - Time Projection Chamber (TPC)
  - (30cm)$^3$
cubic TPC
  - Up to 5 bar.
  - Micromegas + GEM gas amplification
  - Collection on $x, y$ strips, pitch 1 mm.
  - AFTER chip digitization, up to 50 MHz.
  - Scintillator / WLS / PMT based trigger

Time Projection Chambers

Angular resolution improvement

Polarisation

\( \lambda = 0.15 \)

Minimum Detectable Polarization (%) vs Energy (MeV)

TeVPA 2016 (12-16 September 2016)
e-ASTROGAM

- Sub MeV – GeV domain, polarimetry
- Compton and pair conversion telescope
- Detector
  - Double sided Silicon strip (DSSD) tracker
  - 3D imaging scintillator CsI(Tl) calorimeter read out by Si drift diodes
  - Plastic anticoincidence shield read out by SiPM
- Using technology heritage from existing satellites
- Proposed as ESA M5 mission
- Similar concept proposed as NASA MIDEX (ComPair)

```
Tracker
Calorimeter
Tracker
Calorimeter
```

- Plastic anticoincidence system to veto charged-particle induced background

```
Neutrino:Ta:scheff!for!the!e%ASTROGAM!Collabora:on!!
```

**Measurement principle**

- **Pair event**
  - Silicon tracker
  - Scintillator calorimeter

- **Compton event**
  - Plastic anticoincidence system

**Diagram notes**

- Pair event and Compton event interactions
- Angular correlation in the detector

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e-ASTROGAM hardware

- **Tracker**: 56 layers of 4 times 5×5 DSSDs (5600 in total) of 500 μm thickness and 240 μm pitch
- DSSDs bonded strip to strip to form 5×5 ladders
- Light and stiff mechanical structure
- Ultra low-noise front end electronics

- **Calorimeter**: 8464 CsI(Tl) bars coupled at both ends to low-noise Silicon Drift Detectors
- **ACD**: segmented plastic scintillators coupled to SiPM by optical fibers
- **Heritage**: AGILE, Fermi/LAT, AMS-02, INTEGRAL, LHC/ALICE...
e-ASTROGAM science potential

- Improve angular resolution close to the Compton physical limits

Simulation of the Cygnus region in the 1 – 3 MeV energy band using the e-ASTROGAM PSF, from an extrapolation of the 3FGL source spectra to low energies.
Some other projects

**Gamma-400**
- Fermi/LAT-like with increased spacing between tracker and calorimeter
- Better angular resolution
- Poorer sensitivity
- Status unclear

**HERD**
- Primarily a particle detector (like CALET, DAMPE)
- GeV (- TeV) domain
- 3-D cubic calorimeter surrounded by microstrip silicon trackers from five sides
- Weight limited to 2 tons (half of Fermi-LAT)
- Will be placed aboard Chinese space station (2020+)

**Pangu**
- Few MeV – GeV domain, polarimetry
- Pair conversion telescope
- Tracker combined with magnetic spectrometer to fit into 60 kg payload allocation
- Submitted unsuccessfully to joint ESA/CAS small mission call
Ground-based projects

<table>
<thead>
<tr>
<th>Parameter</th>
<th>CTA</th>
<th>HAWC</th>
<th>HiSCORE</th>
<th>LHAASO</th>
<th>MACE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site(s)</td>
<td>t.b.d.</td>
<td>Sierra Negra (Mexico)</td>
<td>Tunka Valley (Russia)</td>
<td>Daocheng (China)</td>
<td>Hanle (India)</td>
</tr>
<tr>
<td>Altitude (m)</td>
<td>~ 2000</td>
<td>4100</td>
<td>675</td>
<td>4300</td>
<td>4270</td>
</tr>
<tr>
<td>Latitude</td>
<td>t.b.d.</td>
<td>19°N</td>
<td>51.8°N</td>
<td>29°N</td>
<td>32.8°N</td>
</tr>
<tr>
<td>Lifetime (years)</td>
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<td>10</td>
<td>t.b.d.</td>
<td>&gt; 10</td>
<td>t.b.d.</td>
</tr>
<tr>
<td>Energy range (TeV)</td>
<td>0.02–300</td>
<td>0.1–100</td>
<td>50–10 000</td>
<td>0.1–1000</td>
<td>t.b.d.</td>
</tr>
<tr>
<td>$\Delta E/E$</td>
<td>10%</td>
<td>50%</td>
<td>10%</td>
<td>20%</td>
<td>t.b.d.</td>
</tr>
<tr>
<td>$A_{\text{eff}}$ (m²)</td>
<td>$3 \times 10^6$</td>
<td>30 000</td>
<td>$10^8$</td>
<td>$8 \times 10^5$ (KM2A) $10^6$ (WCDA)</td>
<td>t.b.d.</td>
</tr>
<tr>
<td>Sensitivity (mCrab)</td>
<td>1</td>
<td>50</td>
<td>100</td>
<td>10</td>
<td>t.b.d.</td>
</tr>
<tr>
<td>Field of view</td>
<td>5°–10°</td>
<td>1.8 sr</td>
<td>0.6 sr</td>
<td>1.5 sr</td>
<td>4°</td>
</tr>
<tr>
<td>Angular resolution</td>
<td>0.05°</td>
<td>0.5°</td>
<td>0.1°</td>
<td>0.3°</td>
<td>t.b.d.</td>
</tr>
</tbody>
</table>

- Imaging Air Cherenkov Telescopes (IACTs) have been proven most efficient to study gamma-ray induced atmospheric Cherenkov light (excellent angular resolution, strong background rejection power)
- Drawbacks are low duty cycles (~10%) and narrow fields of view (~5°)
- Performance increase through more telescopes covering a larger area and eventually using SiPM instead of PMTs
- Water Cherenkov Detectors (WCDs) are most successful devices for studying the tails of extended air showers (“tail catcher detectors”)
- While modest in angular resolution and background rejection, they have excellent duty cycles and wide field of view (complementary to IACTs)
- Performance increase through larger surface areas, moving the detector to higher altitude, and improving the detector configuration
- Open access observatories
2. The CTA Observatory

2.2 Telescope Arrays

Figure 2.3 – Artist impression of the southern CTA site, showing the array combining three different sizes of Cherenkov telescopes, covering a multi-km$^2$ area. The combination of a large number of telescopes of different sizes gives CTA tremendous flexibility of operation as well as unprecedented sensitivity and energy range.

Questions. These three telescope sizes are referred to as the Large-Sized, Medium-Sized and Small-Sized Telescopes (LSTs, MSTs and SSTs). The basic characteristics of these telescopes were fixed as requirements based on these early simulations, plus a first very large scale simulation of realistic CTA telescope arrays. Later large scale simulations served to assess the site-dependence of performance (in particular site altitude and geomagnetic field) and to establish appropriate telescope spacing. A final very large (200M HS06 CPU hours, 3 PB disk space) effort was used to perform a final fine-tuning of the layouts, which are presented in Figure 2.4. The chosen layouts may need to be adapted for ease of deployment, in particular for La Palma, which has more complex constraints. All simulation and analysis tools used have been verified on operating Cherenkov telescope arrays and multiple independent chains have been compared at all steps in the process.

Figure 2.4 – Agreed layout of telescopes on the two sites in the southern hemisphere (left) and northern hemisphere (right). The southern site contains more telescopes and covers a larger area. The SST array has a large footprint to provide a very large gamma-ray collection, but with a relatively high energy threshold due to the smaller telescope size. The LSTs have large individual light-collection power to reach low gamma-ray energies, but need only a modest footprint due to the much higher fluxes of low energy gamma-rays.

The LST, MST and SST sub-systems of CTA are designed to be operable independently as well as part of the complete system. It is envisioned that a significant fraction of the observation time will be spent in CTAO gGmbH.
Cherenkov Telescope Array

An Open Observatory

A world-wide endeavour

Improvements everywhere

- Energy Resolution
  - 10% → lines, features
- Sensitivity & Collection Area
  - ×10 → all topics
- Field of View
  - 8" → surveys, extended objects
- Rapid Slewing
  - 20 seconds → transients
- Angular Resolution
  - Few arcminute → morphology
- Energies down to 20 GeV
  - → Cosmology++
- Energies up to 300 TeV
  - → Pevatrons

Figure 2.1

- Illustration of performance goals and associated science drivers.

Figure 2.2

- Expected sensitivity of the baseline CTA Northern and Southern hemisphere arrays in comparison to current instruments. The performance/cost optimisation leads to a reduced high energy capability for the Northern site. The high energy capability is primarily driven by Galactic objects more effectively observed from the South. The flux sensitivity illustrated corresponds to a five standard-deviation detection in five independent bins per decade in energy.

Negotiations are ongoing and are expected to conclude before the end of 2016. The full economic cost of the implementation of the CTA baseline in both hemispheres is €400M (see section 5).

Figure 2.3 provides an illustration of the completed southern array.

The design of the CTA arrays is the result of a multi-step optimisation process. Early studies including semi-analytical estimates and simulations of regular grids of telescopes indicated the need for three telescope sizes to efficiently cover the wide energy range of CTA and address all of the major science...
Large size telescopes

Science drivers
- Lowest energies (< 200 GeV)
- Transient phenomena
- DM, AGN, GRB, pulsars

Characteristics
- Parabolic design
- 23 m diameter
- 370 m² effective mirror area
- 28 m focal length
- 1.5 m mirror facets
- 4.5° field of view
- 0.11° PMT pixels
- active mirror control
- Carbon-fibre arch structure (fast repointing)

Array layout
- South site: 4
- North site: 4

Status
- Some elements prototyped
- First full telescope under construction in La Palma (http://www.lst1.iac.es/webcams.html)
Mid size telescopes

Science drivers
• Mid energies (100 GeV – 10 TeV)
• DM, AGN, SNR, PWN, binaries, starbursts, EBL, IGM

Characteristics
• Modified Davies-Cotton design
• 12 m diameter
• 90 m² effective mirror area
• 1.2 m mirror facets
• 16 m focal length
• 8° field of view
• 0.18° PMT pixels

Array layout
• South site: 25
• North site: 15

Status
• Telescope prototyped (Berlin-Adlershof)
• Prototype cameras under construction (2 types: NectarCAM & FlashCam)
Small size telescopes

**Science drivers**
- Highest energies (> 5 TeV)
- Galactic science, PeVatrons

**Array layout**
- South site: 70
- North site: -

**First CTA light**

**Characteristics**

**SST 1M**
- Davies-Cotton design
- 4 m diameter
- 8.5 m² effective mirror area
- 5.6 m focal length
- 9° field of view
- 0.24° SiPM pixels

**Status**
- Prototype telescope built
- Camera prototype under construction

**ASTRI**
- Schwarzschild-Couder design
- 4.3 m primary diameter
- 1.8 m secondary diameter
- 6 m² effective mirror area
- 2.2 m focal length
- 9.6° field of view
- 0.17° SiPM pixels

**Status**
- Prototype telescope built
- Camera prototype under construction

**GCT**
- Schwarzschild-Couder design
- 4 m primary diameter
- 2 m secondary diameter
- 6 m² effective mirror area
- 2.3 m focal length
- 8.6° field of view
- 0.16° SiPM pixels

**Status**
- Prototype telescope structure built
- Tested with MAPMT-based CHEC camera
Some other projects

**HiSCORE**
- Non-imaging air-shower Cherenkov light-front sampling
- Up to 100 km² area covered
- Wide field of view (~0.6 sr)
- Extend sensitivity to the PeV regime
- Complemented by IACTs and surface & underground stations for measuring muon component of air showers

**LHAASO**
- Hybrid detector array
- Gamma ray detectors
  - Large (4 x HAWC) Water Cherenkov detector array (0.1-30 TeV)
  - Electromagnetic particle detectors and muon detectors (30-1000 TeV)

**MACE**
- 21 m diameter IACT to be installed at Hanle (4270 m a.s.l)
- Design inspired from H.E.S.S. II
Sensitivity: past – present – future

The figure shows the sensitivity of various gamma-ray observatories as a function of energy. The sensitivity is plotted in erg cm$^{-2}$ s$^{-1}$, and the energy is given in eV. Different observatories are represented by different lines, with labels such as AdEPT, Fermi, MAGIC, H.E.S.S., and CALET. The energy range spans from $10^5$ to $10^{16}$ eV, while the sensitivity range is from $10^{-14}$ to $10^{-8}$ erg cm$^{-2}$ s$^{-1}$.
Conclusions

Space-based
- An instrument covering the MeV–GeV energy range has the highest discovery potential (e.g. e-ASTROGAM, ComPair)
- Will enable
  - measurement of pion-bumps characteristic of hadronic accelerators in many sources
  - study of the still elusive low-energy cosmic-ray component
  - observation of gamma-ray lines (nucleosynthesis, de-excitation, $e^+e^-$ annihilation)
  - gamma-ray polarisation measurements

Ground-based
- The Cherenkov Telescope Array will expand on all aspects of current IACTs (sensitivity, energy range, angular resolution)
- Will enable
  - WIMP detections from few 100 GeV to few TeV
  - search of PeVatrons in the entire Galaxy
  - measurement of sub-minute variability in AGN
  - comprehensive population studies of particle accelerators
  - studies of particle acceleration in and particle propagation near individual sources