The future of gamma-ray astronomy

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Observing gamma rays
History of gamma-ray astronomy

Number of detected sources in red

- Ferrmi
- > 3000
- 198
- HAWC
- MILAGRO
- Thémistocle
- SMM
- CGRO
- COMPTEL
- EGRET
- COS-B
- 25
- Whipple
- H.E.S.S.
- CELESTE
- MAGIC
- VERITAS
- Ooty
- AERE
- Harwell garbage bin Observatory
- 1960: balloons, 1
- 1968: OSO 3
- 1970: Explorer XI, 25
- 1980: HEAO 3, 2
- 1990: SAS 2, 271
- 2000: CGRO, 32
- 2010: INTEGRAL, > 3000

MeV GeV TeV

13th Rencontres du Vietnam (23-29 July 2017)
## 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
- 2000: First SNR
- 2003: $^{60}$Fe lines from Galaxy
- 1993: Galactic origin of cosmic rays
- 1992: Diffuse LMC emission
- 1981: 25 point-like sources
- 1978: First blazar
- 1974: Crab pulsar
- 1972: Diffuse Galactic emission
- 1961: 22 photons > 50 MeV

### 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
- 2002: First starburst galaxies
- 2009: First millisecond pulsars,
- First starburst galaxies
- 2008: Crab pulsar
- 2005: First binary
- 2004: First resolved SNR
- 2002: First unidentified TeV source
- 2000: First SNR

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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
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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
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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>
</tr>
</thead>
<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>
<td>–</td>
<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>
<td>0.01–5</td>
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<td>Ref. energy (GeV)</td>
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<td>0.1</td>
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<td>100</td>
<td>100</td>
<td>0.1</td>
<td>100</td>
<td>1</td>
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<tr>
<td>$\Delta E/E$</td>
<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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<tr>
<td>Sensitivity (mCrab)</td>
<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>
</tr>
<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>
</tr>
<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**
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)

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Pair event
Compton event

Silicon tracker
Scintillator calorimeter
Plastic anticoincidence system

\[ \theta \]

\[ \gamma \]

\[ \gamma \]
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.

V. Tatischeff for the e-ASTROGAM Collaboration

28th Texas Symposium

13–18 December 2015

13th Rencontres du Vietnam (23-29 July 2017)
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

13th Rencontres du Vietnam (23-29 July 2017)
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>Paranal (Chile) / La Palma (Spain)</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>2150 / 2200</td>
<td>4100</td>
<td>675</td>
<td>4300</td>
<td>4270</td>
</tr>
<tr>
<td>Latitude</td>
<td>-24.6° / +28.8°</td>
<td>-</td>
<td>19°N</td>
<td>51.8°N</td>
<td>29°N</td>
</tr>
<tr>
<td>Start of operations</td>
<td>2023</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lifetime (years)</td>
<td>30</td>
<td>10</td>
<td>t.b.d.</td>
<td>2020?</td>
<td>2016</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)</td>
<td>$10^6$ (WCDA)</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
Cherenkov Telescope Array
All Sky coverage

South + North

>60° zenith
45°-60°
30°-45°
Cherenkov Telescope Array

An Open Observatory

A world-wide endeavour

Improvements everywhere
Planned surveys: a deep view of the high-energy Universe

- Full galactic plane (1620 h)
- Deep survey of the Galactic Centre region (825 h)
- The Large Magellanic Cloud (340 h)
- One-pi extragalactic survey down to 6 mCrab (500 h)
Large size telescopes

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

Characteristics
- 23 m diameter
- 370 m² effective mirror area
- 28 m focal length
- 4.5° field of view

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

Status
- Some elements prototyped
- Telescope prototype under construction in La Palma
  (http://www.lst1.iac.es/webcams.html)
Medium size telescopes

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

Characteristics
- 12 m diameter
- 90 m² effective mirror area
- 16 m focal length
- 8° field of view

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**
- 4 m diameter
- 7.5 m² effective mirror area
- 5.6 m focal length
- 9° field of view

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

**Characteristics**
- 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

**Status**
- Prototype telescope built
- Camera prototype installed

**Characteristics**
- 4 m primary diameter
- 2 m secondary diameter
- 6 m² effective mirror area
- 2.3 m focal length
- 8.6° field of view

**Status**
- Prototype telescope built
- Tested with MAPMT-based CHEC camera

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Some other projects

**HiSCORE**
- Non-imaging air-shower Cherenkov light-front sampling
- Up to 100 km$^2$ 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 MAGIC
Sensitivity: past – present – future
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