Exploring the Universe with High-Energy $\gamma$-rays

Benoît Lott, SLAC/CENBG
Specifity of high-energy gamma-ray astronomy

**Extended domain:** 30 keV-30 TeV  9 orders of magnitude

high-energy $\gamma$- rays: $E>30$ MeV
Few photons: $N(E) \sim E^{-2}$

No focalization possible: Photons don’t reach ground (atmosphere is $27 \times 10^3$ thick): electromagnetic shower produced in the atmosphere can be detected.

2 types of detectors:

- Space-based telescopes: “low energy” ($E < 10 \ GeV$), no telescopes in operation since 2001!
- Ground-based Cherenkov telescopes: “high energy” ($E > 250 \ GeV$).

The $10 \ GeV$ - $100 \ GeV$ domain remains little or not explored.

No instrument with large field of view operating at $E > 10 \ GeV$.
GLAST
(Gamma-ray Large Area Space Telescope)
LAT (Large Area Telescope)
30 MeV-300 GeV

Si-W tracker
pitch = 201 μm
12 × 2.5% X₀
+ 4 × 25% X₀

CsI Calorimeter
8.6 X₀   8 × 12 bars
2.0 × 2.8 × 35.1 cm

Pair conversion telescope
16 towers
• Veto
• Tracker
• Calorimeter

ACD
scintillator tiles
0.9997 efficiency

Benoît Lott, SLAC/CENBG
J. R. Huizenga Symp.
The LAT performance

<table>
<thead>
<tr>
<th></th>
<th>EGRET</th>
<th>GLAST</th>
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<tbody>
<tr>
<td>Detector technology</td>
<td>Spark chambers+</td>
<td>Si-strips+</td>
</tr>
<tr>
<td>NaI calorimeter</td>
<td>20 MeV-30 GeV</td>
<td>20 MeV-300 GeV</td>
</tr>
<tr>
<td>Energy range</td>
<td>10%</td>
<td>10%</td>
</tr>
<tr>
<td>Effective area</td>
<td>1500 cm²</td>
<td>8000 cm²</td>
</tr>
<tr>
<td>Deadtime per photon</td>
<td>100 ms</td>
<td>20 μs</td>
</tr>
<tr>
<td>Field of view</td>
<td>0.5 sr</td>
<td>2.4 sr</td>
</tr>
<tr>
<td>Angular resolution (PSD)</td>
<td>5.8° at 100 MeV</td>
<td>3° at 100 MeV</td>
</tr>
<tr>
<td>Source location determination</td>
<td>5°-30°</td>
<td>30°-5°</td>
</tr>
<tr>
<td>Sensitivity (&gt;100 MeV)</td>
<td>10⁻⁷ cm⁻² s⁻¹</td>
<td>4 10⁻⁹ cm⁻² s⁻¹</td>
</tr>
<tr>
<td>Power</td>
<td>160 W</td>
<td>650W</td>
</tr>
<tr>
<td>Orbit</td>
<td>350 km/ 28.5°</td>
<td>550 km/ 28.5°</td>
</tr>
<tr>
<td>Mass</td>
<td>1810 kg</td>
<td>3000 kg</td>
</tr>
</tbody>
</table>

4 10⁻⁹ γ cm⁻² s⁻¹ for 1 year
Response of the LAT calorimeter to:

- relativistic heavy ions
  (FRS/GSI)

- electromagnetic showers
  (CERN-SPS)

80 GeV e+ 1.5 $X_0$

Quenching factor = $k \frac{L_{\text{meas}}}{E_{\text{calc}}}$
HESS

- in operation in Namibia since 2004
- main partners are Germany and France
- energy threshold: 100 GeV
# A little history

<table>
<thead>
<tr>
<th>Year</th>
<th>Mission</th>
<th>$A_{\text{eff}}$ (cm$^2$)</th>
<th>Energy range</th>
<th>Life time</th>
<th>Detection</th>
</tr>
</thead>
<tbody>
<tr>
<td>1967</td>
<td>OSO3</td>
<td>4</td>
<td>$&gt;50$ MeV</td>
<td>15 months</td>
<td>Diffuse Emission</td>
</tr>
<tr>
<td>1972</td>
<td>SAS2</td>
<td>540</td>
<td>20 MeV-1 GeV</td>
<td>7 months</td>
<td>Crab, Vela, Geminga</td>
</tr>
<tr>
<td>1975</td>
<td>COSB</td>
<td>50</td>
<td>30 MeV-5 GeV</td>
<td>7 years</td>
<td>25 sources</td>
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<tr>
<td>1991</td>
<td>EGRET</td>
<td>1500</td>
<td>30 MeV-10 GeV</td>
<td>9 years</td>
<td>271 sources</td>
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<tr>
<td>2007</td>
<td>GLAST</td>
<td>10000</td>
<td>30 MeV-300 GeV</td>
<td>5(10) years</td>
<td>9000 sources?</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Year</th>
<th>Telescope</th>
<th>Threshold Energy</th>
<th>Detection</th>
</tr>
</thead>
<tbody>
<tr>
<td>1989</td>
<td>Whipple</td>
<td>250 GeV</td>
<td>Crab</td>
</tr>
<tr>
<td>1992</td>
<td>Whipple</td>
<td>250 GeV</td>
<td>Mkn421</td>
</tr>
<tr>
<td>1995</td>
<td>Whipple</td>
<td>250 GeV</td>
<td>Mkn501</td>
</tr>
<tr>
<td>2002</td>
<td>Whipple CAT</td>
<td>250 GeV</td>
<td>1ES 1426+428, 1ES 1959+650</td>
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<tr>
<td>2004-6</td>
<td>HESS</td>
<td>100 GeV</td>
<td>&gt;30 sources</td>
</tr>
</tbody>
</table>
The high-energy gamma-ray sky

EGRET sky map for $E>100$ MeV (Seth Digel)
60% of photons from Galactic Diffuse Emission
30% of photons from Extragalactic Diffuse Emission (isotropic)
fairly large discrepancy: “GeV-excess problem”

IC: Inverse Compton
bremss: bremsstrahlung
EB: Extragalactic background

Galactic Diffuse Emission
3rd EGRET Catalog: 271 sources
170 unidentified!
Pulsars

Neutron stars: Endpoint of evolution of massive stars (1.4 M< M< 3 M).

Properties: R=10 km, M=1 M, nuclear density, B~10^{12} G, superfluid interior, deconfined -quark core?

«Cosmic lighthouse», T=10 ms – 3 s >1000 known in radio, 8 in ~150 SNR, ~12 known associations.

The three brightest -ray sources are pulsars: Geminga (400 ly), Crab (7000 ly), Vela (800 ly).

The electron «wind» of young pulsars can energize the ejecta: nebula or «plerion», like the Crab nebula.

Geminga

Crab

«Galactic anticenter»

EGRET
Pulsar phasograms
Radio: coherent emission
High-energy emission: two competing classes of models assuming different locations of the accelerating cavity within the magnetosphere
- polar cap (small $\Omega_{\text{em}}$)
- outer gap (large $\Omega_{\text{em}}$)
Expansion on July 4, 1054

distance: $6.3 \times 10^3$ light years

$T_{\text{pulsar}} = 33$ ms

Plerion
(Wind-Powered Nebula)
First-order Fermi process
Supernova Remnants (SNRs)

Some are « shell » SNRs (no active nebula) known acceleration sites of electrons
Example: Gamma Cygni

**EGRET:** several sources compatible with SNRs but:

- **persistent location problems**
- **absence of clear $\pi^0$ peaks**

![Gamma Cygni image](image.png)
Supernova remnants shine at TeV energy, but whether this emission is due to $\pi^0$ decays remains unclear. GLAST will help sort out this issue.
Active Galaxy Nuclei (AGNs) - Blazars

A few % of all galaxies are “active”, $L_{\text{nucleus}} > L_{\text{star}}$
95% are radio-quiet: “Seyfert”
5% are radio-loud: “quasars” or “blazars”

$1 \, M_\odot \sim 10^{54} \, \text{erg}$
Superluminal motion

VLBI observation: $v_{\text{app}} = 4 \, c$!
Jets in AGNs

Problem: Compact sources, high luminosity
High **optical thickness** for pair production

\[
t = \frac{s_T}{5} \frac{L_{1/x}}{4pRm_e c^3}
\]
Blazar morphology
Core of Galaxy NGC 4261

Hubble Space Telescope
Wide Field / Planetary Camera

Ground-Based Optical/Radio Image

HST Image of a Gas and Dust Disk

380 Arc Seconds
88,000 LIGHTYEARS

17 Arc Seconds
400 LIGHTYEARS
How to explain rapid variability

Modulation of relativistic flows - faster shell ($\Gamma_1$) catches up with the slower one ($\Gamma_2$)

$e^-e^+$ (and possibly smaller fraction of $p$) are accelerated in the shock, and emit Synchrotron/Inverse Compton radiation.
Blazar Spectral Energy Distributions

Spectra exhibit two humps, corresponding to synchrotron emission and IC scattering.

Emission over 17 decades in energy!

Variability studies provide a wealth of information on time lags between bands → acceleration/cooling competition.

Spada et al. Mrk421
Open issues about blazars

- mechanism of extraction of energy from the BH and production of jet
- mechanism and sites of particle acceleration
- identification of the physical parameters driving the observational properties (LBL vs HBL): accretion rate?
- environment inducing the high-energy component
  Synchrotron Self-Compton vs External Compton
- Jet contents (leptonic or hadronic)
- luminosity function

**EGRET:** 100 Blazars
(0.03 < z < 2.3)

**GLAST:** > 4000 Blazars
Extragalactic Background Light

Hubble Deep Sky Survey

Direct measurement difficult due to large foreground components

\[ \gamma + \nu_{\text{IR}} \rightarrow e^+ e^- \]

threshold: \( eE (1 + z)^2 (1 - \cos \theta) > 2 (m_e c^2)^2 \)

\[ e_{\nu} = \frac{500 \text{GeV}}{E_{\text{GeV}} (1 + z)^2} \quad \text{or} \quad \lambda_{\mu m} = 1.2 \frac{E_{\text{GeV}} (1 + z)^2}{500 \text{GeV}} \]

\[ F_{\nu}^{\text{obs}} = F_{\nu}^0 \exp(-t(\nu, z)) \]

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Astroparticle Physics

Extragalactic Diffuse Background
Comes from non-resolved AGNs but a component could correspond to the decay of relic particles e.g. WIMPS

Stable supersymmetric candidate neutralino with $50 \text{GeV} < M_\chi < 100 \text{GeV}$

$\chi\chi \to \gamma X$ or $\chi\chi \to \gamma\gamma$

The large number of blazars detected by GLAST will enable to pin down the (non-accounted for) contribution.

Galaxy center

Presence of a line at $E_\gamma = M_\chi$?
First detected in 1967, disclosed in 1973 ‘burst’:
100ms - 100s (ms substructure)

Afterglow:
- a few days
- flux: $10^3 - 10^4$ times higher than AGN

Isotropy:
- large galactic halo or cosmological distances?

Galactic origin long favored because of energy requirements...

More than 100 models, some very exotic...

Gamma-Ray Bursts (GRBs) 1997: Major breakthrough

BeppoSax enables the discovery of an optical counterpart:
- host galaxy: $z=0.695$

GRBs are the most powerful phenomena since the Big Bang: up to $10^{54}$ erg/s (unbeamed)
Light curves and energy spectra

Great variety of light curves!

Band et al.:

\[ N(E) \propto \begin{cases} 
E^a e^{-E/E_p} & \text{for } E < E_p \\
E^\beta & \text{for } E > E_p 
\end{cases} \]

\[-1.0 \leq a \leq -0.5 \quad 100\text{keV} \leq E_p \leq 200\text{keV}\]

\[-3.0 \leq \beta \leq -2.0\]
Finding the optical counterpart enables the distance to be inferred (emission or absorption lines) and thus the absolute luminosity to be determined.
Progenitors
(disentangled by positions in host galaxies, light curve)

Long bursts: collapse of a massive star: hypernova

Short bursts:
coalescence of compact objects
(neutron stars, BH)

Breaking news!
(HETE, Swift)
The Fireball Model

Explosion of stellar origin (galaxy z~1): expanding «fireball» of $e^+$, $e^-$, and a few baryons. Collimated jet with $10^{-4}\ M$ and ~100–1000.

Break in the afterglow's light curve proves the beaming (jet = 1/break).

Beaming alleviates the energetics problem by a factor.

Shocks between colliding «shells»: acceleration of $e$, baryons (UHECRs)?

- ray emission via synchrotron+inverse Compton scattering

The Fireball Model

- Pre-Burst
- Shock Formation
- Afterglow
- LOCAL MEDIUM

$E \sim 10^{53}$ ergs
$T = 0\ s$
$R = 10^6\ cm$

$T \sim 10^2\ s$
$R \sim 3 \times 10^{12}\ cm$

$\Gamma \sim 10^3$

$T \sim 3 \times 10^3\ s$
$R \sim 10^{14}\ cm$

$T \sim 10^6\ s$
$R \sim 3 \times 10^{16}\ cm$
GRBs as seen by EGRET

30 (long) GRBs including 4 with $E > 100$ MeV

EGRET hampered by long dead time (100ms)

Energy spectrum for EGRET’s 4 high-energy GRBs
Studying GRBs with GLAST

LAT+GRM: coverage from 20 keV to 300 GeV
200 GRBs per year!
Strong contraint on $\Gamma$ via the highest energy measured

Other programs:
all other wavelengths (HETE2, SWIFT, ECLAIR, TAROT…)
« neutrinos bursts »: probe hadronic interactions
Ultra High Energy Cosmic Rays? GRBs may solve the « energetics + $E_{\text{loss}}$ » problem
gravitational waves: coalescence of binary stars

Test of Quantum Gravity
$v \sim c \left(1 - \frac{\xi E}{E_{QG}}\right) \quad E_{QG} \sim 10^{19} \text{GeV}$
Other new windows on the High-Energy Universe

- Gravitational waves (Ligo, Virgo, Lisa…)
- Neutrino astronomy (Ice Cube, Antares…)
- UHECR (Auger…)

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Happy Birthday, John!