Gamma-ray Astronomy from Space

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Plan

- Introduction: A very demanding space astronomy
- The gamma-ray domain
- Why gamma-ray astronomy?
- Observing in the gamma-ray domain
  Operating beyond the atmosphere
  Collecting gamma rays
- Historical milestones
Plan (contd)

- How to detect gamma-ray photons?
- How to make astronomy with gamma-ray photons?
  Coded-mask
  Study of interaction processes
- How to produce gamma rays in the Universe?
  Electromagnetic emission mechanisms
  Nuclear gamma-ray line emission mechanisms
  Particle annihilation and decay
- Future prospects
Astronomy of the utmost

Space gamma-ray astronomers face a threefold handicap:

- Gamma rays cannot be reflected ($\lambda \ll$ inter-atomic distances) $\rightarrow$ detection area $\equiv$ collecting area (with the exception of Laue diffraction concentrators)

- At equal radiation power, celestial bodies active in gamma rays radiate much less photons $\rightarrow$ very long observing times (days, weeks, ...)

- When operating in space, gamma-ray “telescopes” are exposed to cosmic particles $\rightarrow$ intense background
radio, IR, visible, UV, soft X-rays

hard-X rays
gamma rays

radio, IR, visible, UV, soft X-rays
The gamma-ray domain

Adopted lower limit of the gamma-ray domain: $E_\gamma = 30$ keV

- $E_\gamma = 30$ keV $\rightarrow \lambda = 4.133 \times 10^{-11}$ m $\rightarrow \nu = 7.254 \times 10^{18}$ Hz

Although arbitrary, this limit does express profound astrophysical and experimental realities:

- At $E_\gamma \geq 30$ keV, thermal emission mechanisms give way to non-thermal emission mechanisms
- Problems to concentrate photons at $E_\gamma \geq 30$ keV $\rightarrow$ telescopes radically different from those designed to detect sources at other wavelengths
- Cosmic particles induce within space devices parasitic background which severely limits the sensitivity of any telescope operating at $E_\gamma \geq 30$ keV
At longer $\lambda$, most celestial bodies are the site of thermal emission, more or less comparable to that of a blackbody. In order to sustain blackbody radiation, a celestial body must fulfill the following two conditions:

- Its luminosity cannot exceed the Eddington limit beyond which the radiation pressure exceed gravity

$$4 \pi R^2 \sigma T^4 \leq 10^{38} \frac{M}{M_{\odot}} \text{ erg s}^{-1}$$

- Its radius must exceed its Schwarzschild radius

$$R > 2 \frac{MG}{c^2}$$

→ its radius should be: $R < 475 \ T_7^{-4} \text{ km}$
Why gamma-ray astronomy?

- The **specific character** of the emission processes
  Interaction of accelerated electrons with matter, magnetic fields and photon fields
  Decay of unstable particles
  Matter-antimatter annihilation
  Nuclear de-excitation

- The **diversity** of the emission sites
  High-temperature plasmas confined by compact objects (neutron stars, black holes)
  Relativistic plasmas
  Diluted media crossed by accelerated particles
  Media “contaminated” by radioactive species

- The **extreme luminosity** of gamma-ray sources
  High-z Universe
Why gamma-ray astronomy? (contd)

- The penetrating power of gamma-ray photons
  Media optically thick at other $\lambda$
  Regions masked at other $\lambda$, as the Galactic center

Visible band

Soft gamma rays (40-80 keV)
Operating beyond the atmosphere

Atmospheric transmission reduced by 50% for stratospheric balloons.
Operating beyond the atmosphere (contd)

- Devices supposed to work aboard space vehicles have to be designed in view of:
  - high reliability
  - low power consumption and limited data flow

- Each equipment is to be constructed following very constraining rules and has to be qualified after:
  - vacuum and thermal tests
  - vibration and acoustic tests
  - electromagnetic compatibility tests

- Extensive pre-launch calibrations are mandatory in case of gamma-ray telescopes whose performances are an extremely complex function of the energy and incidence angle of the incident photons
Qualification tests

- INTEGRAL thermal model inside the Sun simulator
- INTEGRAL flight model on shaker
Ground calibrations

As an example, a brief report on the recent calibrations of the INTEGRAL spectrometer SPI performed in April 2001 at Bruyères-le-Châtel (CEA/DAM)

- The objective was to calibrate SPI...
  ...
  ...from both spectroscopy and imaging aspects
  ...
  ...over the whole SPI energy range (20 keV-8 MeV)

- The main issues were...
  ...
  ...no radioactive source to radiate at $E_\gamma > 2$-3 MeV
  ...
  ...calibrating imaging properties need parallel beams

- The adopted solutions were...
  ...
  ...de-excitation of nuclides excited by fast protons
  ...
  ...distant high-intensity sources
SPI in the clean room built inside the 4 MV accelerator
Van de Graaf device to accelerate protons up to 4 MeV
proton + $^{13}\text{C} \rightarrow ^{14}\text{N} \text{ excited} \rightarrow ^{14}\text{N} + \text{gamma-ray photon}$
Low intensity gamma-ray sources
Very high intensity gamma-ray sources
Monday April 16 2001, Saclay, Osiris nuclear reactor fabrication of a $^{24}\text{Na}$ gamma-ray source (half-life 15 h)
Wednesday April 18 2001, Bruyères-le-Châtel
Setting-up of the source lead container (500 kg)
Wednesday April 18 2001, Bruyères-le-Châtel
Opening of the source container
The “sky-image” reconstructed with the $^{24}\text{Na}$ source
Once in orbit, experimental devices are exposed to high fluxes of accelerated particles.

In case of a gamma-ray telescope, accelerated particles induce a severe background that heavily affects the telescope sensitivity...

...in producing within detectors ionizing effects similar to those induce by cosmic gamma rays...

...in producing secondary gamma rays within the instrument itself and its space platform.

In such a context, gamma-ray observations appear as prohibitive as would be astronomical observations in the visible performed in broad daylight!
Collecting gamma-ray photons

Devices able to focus gamma radiation come up against great difficulties since inter-atomic distances within solids (~ few angstroms) are larger than the wavelength of gamma radiation → collecting area ≡ detection area

- The sensitivity increases only in proportion of the square root of the observing time or detection area
- Increase of the sensitivity of a gamma-ray telescope implies observations of very long duration or detectors of very large size, two conditions which are not always compatible with the constraints of a space mission

Bringing into operation devices able to focus gamma rays is one of the major challenges for gamma astronomers
Towards a gamma-ray lens

Plane parallel crystals which intercept a beam of very short wavelength radiation $\lambda$ act as a 3-D diffraction array.

When entering a crystal under an angle $\theta$, a beam can be diffracted under the same angle $\theta$ defined by the Bragg condition: $2d \sin(\theta) = n\lambda$.

Such a process is known as Laue diffraction.
Historical milestones

1952 Prediction of the high-energy gamma-ray emission of the Galactic disk (Hayakawa)

1958 Inventory of the cosmic sites most likely expected to radiate gamma rays → it includes the Sun, the Crab Nebula, Cyg A (Morrison)

1958 First detection of cosmic gamma rays during the March 28, 1958 solar flare (Peterson & Winckler)

1967 First exhaustive revue devoted to gamma-ray astronomy (Fazio) ...ten years after the launch of Sputnik 1, one had not succeeded in definitely detecting any gamma rays emanating from cosmic sites localized beyond the solar system...
Historical milestones (contd)

1968  Discovery of the high-energy gamma-ray emission of the Galactic disk

1968  Discovery of the soft gamma-ray emission of the Crab nebula


1969  Discovery of the soft gamma-ray emission of the Crab pulsar

1972  Discovery of the high-energy gamma-ray emission of the Crab pulsar


Historical milestones (contd)

1973  First report of the detection of intense gamma-ray bursts of cosmic origin

1975  Launch of the European satellite COS-B devoted to high-energy gamma-ray astronomy


In operation from 1975 until 1982
COS-B achievements

- **Precise spectra** of the high-energy gamma-ray emission of the Galactic disk
- **Discovery** of the high-energy gamma-ray emission of the quasar 3C 273

Paul et al. 1978, A&A 63, L31
1978  First precise measurement of a positron annihilation line emission from the GC region

1982  First detection of a nuclear gamma-ray emission from the inner Galaxy
1990 Following a period of little activity (Challenger disaster), the nineties were a golden decade for gamma-ray astronomy owing to a new generation of gamma-ray telescopes aboard GRANAT and CGRO.

- **GRANAT**: In operation from 1990 until 1997
- **CGRO**: In operation from 1991 until 2000
SIGMA/GRANAT achievements

- Gamma-ray studies of accreting stellar black holes
- Contribution to the discovery of microquasars

Goldwurm et al. 1994, Nat 371, 589
Mirabel et al. 1992, Nat 358, 215
SIGMA/GRANAT achievements (contd)

- Discovery of positron annihilation line emission from the black-hole transient GRS1124-68 (Nova Muscae)

Deficit of weak bursts in case of a source population uniformly distributed in an Euclidean space.

GRO/BATSE detection of 2091 GRBs
CGRO achievements (contd)

OSSE map of the 511 keV line from $e^- e^+$ annihilation
CGRO achievements (contd)

COMPTEL map of the Galactic $^{26}$Al emission
CGRO achievements (contd)

EGRET catalog of high-energy gamma-ray sources including tens of blazars
Historical milestones (provisional end)

1997  The advent of the Beppo-SAX era

<table>
<thead>
<tr>
<th>Time</th>
<th>Image Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_B + 6.5 , h$</td>
<td>![Image 1]</td>
</tr>
<tr>
<td>$T_B + 12 , h$</td>
<td>![Image 2]</td>
</tr>
<tr>
<td>$T_B + 52 , h$</td>
<td>![Image 3]</td>
</tr>
</tbody>
</table>

Afterglow of GRB 971214

Fading X-ray source detected in the 1.3-10 keV band within the gamma-ray burst error box by the focusing telescope aboard BeppoSAX satellite

Afterglow in the visible
Interaction processes

- **Photoelectric effect:** Absorption of a photon of energy $E_0$ with ejection of a bound electron of an atom of the detection medium.

  The electron gains a kinetic energy $E = E_0 - E_{\text{BINDING}}$

- **Compton scattering process:** The energy $E_1 (E_1 < E_0)$ of the scattered photon is related to its incident energy $E_0$ and to the scattering angle $\theta$ according to

  $$E_1 = \frac{E_0}{1 - \frac{E_0 (1 - \cos \theta)}{m_e c^2}}$$

- **Pair creation:** A photon of energy $E_0$ with $E_0 > 2m_e c^2$ may create in the intense electric field of a nucleus an electron-positron pair such as $E_0 = E_1 + E_2 + 2m_e c^2$
Diffusive material

Evolution of the aluminum mass attenuation coefficient with the photon energy

- Photoelectric
- Compton
- Pair
Absorbing material

Evolution of the lead mass attenuation coefficient with the photon energy
Detectors

In the detecting media, the electrons ejected or created by the incident gamma rays lose energy mainly in ionizing the surrounding atoms; secondary electrons may in their turn ionize the material, producing an amplification effect.

Most space gamma-ray telescopes consist of detection materials which take advantage of ionization process but the way to measure the total ionization loss differ with the nature of the material.

Commonly used detection devices are...

  ...gas detectors
  ...scintillation counters
  ...semi-conductor detectors
Observing the gamma-ray sky

- **Collimating**: the simplest way

  Collimators are the simplest "optical" devices to determine gamma-ray photon incident direction.

  Collimated telescopes were frequently used in the early 90s, as their simple conception enable the fabrication of very large devices, such as OSSE aboard CGRO.

- **Coded aperture**: a more clever way

  Coded aperture (inspired from pinhole camera) combines good angular resolution, large acceptance angle and wide collecting area at the cost of a complex imaging process.
Coded-aperture principle

A coded mask (array of opaque blocks) is disposed so that a point source at infinity projects on a position sensitive detector a pattern characteristic of the source direction
Coded mask

Position sensitive detector

Source 1 at infinity
Source 2 at infinity

Coded mask

Position sensitive detector
Coded-aperture in equations

Let $M$ be the distribution of opaque and transparent mask elements and $S_\gamma$ the distribution of the source intensities in the field of view, the detected signal is $D = M * S_\gamma$ (1) where $*$ stands for the cyclic convolution operator.

To construct an image $W$ of the sky in an unique way, the response function $M$ should be invertible; this condition holds if we can derive a matrix $G$ such as $G * M = \delta$.

In this case, the sky image is $W = G * D$ (2) equivalent to $W = G * M * S_\gamma$ (3) implying indeed $W = S_\gamma$ since $G * M = \delta$.

The Uniformly Redundant Array (URA), as described by Fenimore & Cannon in 1978 (Applied Optics 17, 337), meets the above conditions and minimize the background contribution which was neglected in equations (1) to (3).
SIGMA: The precursor

First space coded mask telescope to operate in the 35 keV to 1.3 MeV band; angular resolution: 13 arc minutes
It works!

observation

transmission

deconvolution
INTEGRAL: The masterpiece

Imaging and spectroscopy in the 15 keV to 10 MeV band with source monitoring in the X-ray and visible bands
IBIS, an imager with spectral abilities
Spectral-imaging of Vela “junior”

Name: RXJ0852-4642  Age: 1300 years  Distance: 200 pc

COMPTEL image in the 1.156 MeV $^{44}$Ti line

Simulated IBIS image in 68-78 keV $^{44}$Ti lines

ROSAT: 0.1-2.4 keV

ROSAT: 1.3-2.4 keV
SPI, a spectrometer with imaging abilities
SPI studies of SN Ia

Simulated SPI spectra (integration time $10^6$ s) for a detonation and a deflagration SN Ia at 5 Mpc (Gómez-Gomar et al. MNRAS 295, 1, 1998)

SPI will be in a position to detect a detonation SN Ia up to 16 Mpc

$^{56}$Co (847 keV)
In taking into account the **Compton scattering** process

A Compton telescope features two position sensitive detectors:

Layer 1: made of diffusive material to scatter the incident gamma ray
Layer 2: made of absorbing material to absorb the scattered photon

Both incoming photon incidence angle $\Phi$ and energy $E_0$ can be derived from the measured energy deposits $E_1$ and $E_2$ in layers 1 and 2 and from the angle $\Psi$ of the scattered photon according to:

\[ E_0 = E_1 + E_2 \]
\[ \Phi = \psi + \theta \]
\[
\cos \theta = 1 - \frac{E_1 m_e c^2}{E_0 E_2}
\]
Observing the gamma-ray sky (contd)

In taking into account the pair creation process:

Incident photon whose energy $E_\gamma > 2m_e c^2$ i.e. $E_\gamma > 1.022$ MeV, can induce an $e^-e^+$ pair in the intense electric field close to an atomic nucleus.

Particle trajectories do not markedly deviate from the photon direction as soon as the photon energy $E_\gamma >> 2m_e c^2$

Mean deviation $\theta$ is: 

$$\langle \theta^2 \rangle = \frac{1}{q (E_\gamma, E_e, Z)} \frac{m_e c^2}{E} \ln \left( \frac{E}{m_e c^2} \right)$$

In case of $E_\gamma = 100$ MeV, the mean deviation $\theta \sim 1.5^\circ$
High-energy gamma rays with GLAST

- Launched in 2005
- Lifetime: 5 y (goal 10 y)
- Payload to be built by a wide collaboration of Astrophysics and Particle Physics institutes in USA, France, Italy, Germany, Sweden and Japan

Energy range: 10 MeV to > 300 GeV
Field of view: > 3 sr
Source location accuracy: 30” - 1’
Energy resolution (1 σ): 2% (> 10 GeV)
Sensitivity (2-y survey): 2 $10^{-9}$ cm$^{-2}$ s$^{-1}$ (> 100 MeV)
GLAST: Thousands of blazars

- Zoom on the Virgo region E > 1 GeV
- Detection of 4500 blazars in a 2 years survey

Simulated > 100 MeV skymap (one year survey)
AGILE: The GLAST precursor

- Italian small space mission to be launched in 2003
  Life-time > 3 years

- One single silicon-strip tracker made of 14 planes of $38 \times 38$ cm$^2$

Energy range: 30 MeV to 50 GeV
Field of view: > 3 sr
Source location accuracy: 5' - 20'
Energy resolution (1 $\sigma$): 100% (at 300 MeV)
Sensitivity ($5\sigma$, $10^6$ s): $6 \times 10^{-9}$ cm$^{-2}$ s$^{-1}$ MeV$^{-1}$
Electromagnetic emission mechanisms

Accelerated electrons radiate gamma-ray photons of all energies through electromagnetic interactions with nuclei or magnetic fields

- **Bremsstrahlung**: at work mainly in the interstellar medium

- **Synchrotron radiation**: at work in supernova remnants, spin powered pulsars, gamma-ray bursts, blazars, ...

High-energy electrons may also interact with low-energy photons so that the photon energy is roughly multiplied by the square of the electron Lorentz factor

- **Inverse Compton effect**: at work in the interstellar medium, supernova remnants, accretion disks, blazars
Spin powered pulsars
Accreting black holes

Laurent & Titarchuk (1998)

Accretion disk

Emerging spectrum

Flux (arbitrary unit)

energy (keV)

non-relativistic treatment

relativistic treatment
Leptonic jet models require **Compton scattering** of soft photons by relativistic electrons in the jet; soft photons originate as **synchrotron** emission from within the jet as in the synchrotron-self-Compton process (Maraschi et al.)
**Gamma-ray line emission mechanisms**

**Nuclear lines**, soft gamma-ray lines that result from the de-excitation of excited nuclei produced by:
- Radionuclide disintegration
- Nuclei collision
- Neutron capture

**511 keV line** from the annihilation of positrons, the end products of many high-energy astrophysical processes:
- $\beta^+$ radioactivity
- Decay of $\pi^+$ induced by $p-p$ interactions
- Hot plasmas favoring relations such as $\gamma + \gamma \leftrightarrow e^- + e^+$

**Cyclotron lines**, pseudo soft gamma-ray lines produced in the close vicinity of highly magnetized neutron stars, the first being at $E = 11.6 \times 10^{12}$ keV
### Most Detectable Disintegration Lines

<table>
<thead>
<tr>
<th>Decay chain</th>
<th>Most favorable sites</th>
<th>Lifetime (y)</th>
<th>Energy (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{56}\text{Ni} \rightarrow ^{56}\text{Co} \rightarrow ^{56}\text{Fe}$</td>
<td>Supernovae</td>
<td>0.31 (a)</td>
<td>0.847</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.238</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.771</td>
</tr>
<tr>
<td>$^{57}\text{Co} \rightarrow ^{57}\text{Fe}$</td>
<td>Supernovae</td>
<td>1.1</td>
<td>0.122</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.136</td>
</tr>
<tr>
<td>$^{22}\text{Na} \rightarrow ^{22}\text{Ne}$</td>
<td>Novae</td>
<td>3.8</td>
<td>1.275</td>
</tr>
<tr>
<td>$^{44}\text{Ti} \rightarrow ^{44}\text{Sc} \rightarrow ^{44}\text{Ca}$</td>
<td>Supernovae</td>
<td>70 (a)</td>
<td>0.068</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.078</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.156</td>
</tr>
<tr>
<td>$^{26}\text{Al} \rightarrow ^{26}\text{Mg}$</td>
<td>AGB &amp; WR stars</td>
<td>1.1 $10^6$</td>
<td>1.809</td>
</tr>
<tr>
<td></td>
<td>novae, supernovae</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{60}\text{Fe} \rightarrow ^{60}\text{Co} \rightarrow ^{60}\text{Ni}$</td>
<td>Supernovae</td>
<td>2.2 $10^6$ (a)</td>
<td>1.173</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.322</td>
</tr>
</tbody>
</table>

(a) Longest lifetime in the case of twofold decay chains
Particle decay

Hadronic interaction generate many secondary particles, some of which decay in emitting high-energy gamma rays.

Decay of $\pi^0$ induced by $p-p$ interactions at work in the interstellar medium.

Electron Bremsstrahlung emission at work in the interstellar medium.

Emission excess $> 1$ GeV: calibration error or new contribution?

Emissivity of the local interstellar medium (Strong & Mattox, 1996)
A fantastic series of space missions

HETE-2 2000
INTEGRAL 2002
AGILE 2003
SWIFT 2003
GLAST 2005

And after, What kind of mission can be looked into?
What kind of telescope?

Coded aperture
Angular res. **
Background *
Field of view **

Compton
Angular res. *
Background **
Field of view ***

Concentrator
Angular res. ***
Background ***
Field of view *
EXIST on the ISS

8 coded aperture telescopes (1 m² each)
Field of view: 40° x 160°
Advanced Compton Telescope
Projects involving a gamma-ray lens

Mission proposed in answer to the CNES announcement of opportunity (03/2002)

Balloon borne prototype first flight in June 2000
847 keV line emission of a SN Ia located at a distance of 30 Mpc

MAX will be in a position to detect a SN Ia up to ~ 70 Mpc