Concepts and Characteristics of High-Energy Astronomical Experiments

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Gamma-ray Astronomy

• Provides information about the most energetic processes and phenomena in the Universe
• Wide variety of different objects and phenomena can be studied
• Unlike common "light", \( \gamma \)-rays do not reflect off surfaces due to their high penetration power
• Universe is found to be largely transparent when viewed in the \( \gamma \)-ray frequency range
Gamma-ray Astronomy

Scientific Objectives

- Neutron Stars
- Galaxies
- Sun
- Black Holes
- Supernovae explosions
- Supernovae remnants

- $\gamma$-ray burst sources
- Cosmic rays
- Physical conditions of source regions
- Chemical evolution of our galaxy
γ-rays are produced throughout the galaxy by several different processes:

- Accelerated charged particles
  - Synchrotron radiation
  - Bremsstrahlung
- e⁻ e⁺ annihilation
- Inverse Compton scattering
- Nuclear transitions
  - π⁰ decay
Interactions

Since γ-rays do not ionize matter along their path they can only be detected after they have interacted with matter through one of the following three processes:

- Photoelectric absorption
- Compton scattering
- Pair production
Cross Sections

- Pair Production (> 10 MeV)
- Compton Scattering (0.2-10 MeV)
- Photoeffect (< 100 keV)
- Photon Crosssection Minimum

Graph showing cross sections for different energy ranges.
Photoelectric Absorption

- Photoelectric absorption results from the interaction of γ-rays with bound electrons of the detector material.
- All the energy of the γ-ray is lost in this interaction.
- Provides only information about the energy of the γ-ray and the position, it interacts with the detector material.
- Information about the direction has to be obtained by optical arrangement of the instrument, like limited window of view.
Compton Scattering

- The $\gamma$-ray is scattered off from an electron, transferring only a part of its energy to the electron.
- The $\gamma$-ray continues with reduced energy and changed direction. The energy of the scattered $\gamma$-ray depends on the original $\gamma$-ray energy and the scatter angle $\theta$.

\[
E'_\gamma = \frac{E_\gamma \cdot m_e c^2}{m_e c^2 + E_\gamma \cdot (1 - \cos \theta)}
\]

\[
\theta = \arccos \left[ 1 - m_e c^2 \cdot \left( \frac{1}{E'_\gamma} - \frac{1}{E_e + E'_\gamma} \right) \right]
\]

\[
E_\gamma = E'_\gamma + E_e
\]
Compton Scattering

- Only when the direction of the recoil electron is measured can the arrival direction be uniquely defined.
- Compton scattering provides information about the energy and by kinematics calculation the direction of the $\gamma$-ray.

\[ \begin{align*}
D1 & \quad \gamma \\
\theta & \quad \theta \\
D2 & \quad \gamma' \\
\end{align*} \]
Pair production

- The incident $\gamma$-ray is annihilated in the field of the nucleus, producing an electron-positron pair. The excess of the $\gamma$-ray's energy above that required to produce an electron-positron pair at rest is imparted as kinetic energy to the electron and the positron.
- Pair creation has a threshold at 1.022MeV below which it cannot take place.
Detection of highest energy $\gamma$-rays through secondary radiation from charged particle ($e^- - e^+ - \gamma$) cascades
Cerenkov light

- Whenever a charged particle moves through a transparent medium faster than the local speed of light within this medium (\(\beta n > 1\)) then Cerenkov photons are emitted.
- Secondary particles like electrons from Compton scattering or electron-positron pairs from pair production can cause Cerenkov light.
- Photons are emitted in a cone along the direction of the particle velocity.
- Allows distinction between upward- and downward-moving charged particles.

\[
\cos \theta = \frac{1}{\beta \cdot n}
\]

cone angle: \(\cos \theta = \frac{1}{\beta \cdot n}\)
General problems of γ-ray astronomy

- Low Cosmic Gamma-Ray Fluxes
- Cosmic Gamma-Ray Background
  - Extragalactic Gamma Radiation
  - Galactic Gamma Radiation
- High instrumental background in satellites
- Focussing
- Opaqueness of the Atmosphere
Ground based

- Energetic $\gamma$-rays ($>\sim 10\text{GeV}$) are highly penetrating and will be absorbed in the atmosphere, mainly by creating large particle showers of electrons and positrons.
- Cerenkov light caused by these secondary particles can be used for registration of primary $\gamma$-rays.
- Very diffuse nature of the flash together with the distance of the event (about 20km) requires large optical mirrors for the collection of all the light from the flash.
- Secondary particles reach the ground only for primary $\gamma$-rays above 10TeV (and can be used for detection themselves).

Background
- Cosmic Gamma-ray background
- Atmospheric Gamma-ray background
- Background due showers initiated by other cosmic ray particles (e.g. hadrons)
H.E.S.S.
High Energy Stereoscopic System

- Four telescopes each segmented into 382 mirror facets with a combined area of 107m² (13m in diameter) for one telescope
- Four different views of the same shower enable the reconstruction of γ-direction better than 0.1°
- Impact point can be located with a precision of 10-20m
- Energy precision for a gamma-ray is of about 15%
- Even a single telescope of HESS is the most sensitive instrument in the southern hemisphere.
H.E.S.S.
High Energy Stereoscopic System
H.E.S.S.
High Energy Stereoscopic System

Gamma-ray image of the supernova remnant RX J1713.7-394

Map of the tera-electron-volt γ-ray sky in the region of the Galactic Centre

Right: typical image of an air shower
Left: Cerenkov ‘ring’ of a muon traversing the mirror
MAGIC
Major Atmospheric Gamma Imaging Cerenkov

- Single telescope with a mirror surface of 236m² assembled of nearly 1000 individual mirrors, together resulting in a parabolic dish with 17 m diameter
- Largest collection surface of any existing or projected single gamma-ray telescope world-wide
- Best light collection that has been attempted so far
- A second MAGIC type telescope is under construction in order to monitor multiple sources simultaneously
Spaceborne

• To measure the low γ-ray fluxes spaceborne telescopes must have a large effective area, and long observation times are needed
• Because of their small cross section γ-rays are highly penetrating particles. Therefore thick detectors with a high stopping power are needed

=> normally γ-ray telescopes consist of large heavy detectors

Background

External Background
• Extraterrestrial particle and γ-radiation
• Atmospheric particle and γ-radiation

Internal Background
• Activation of atomic nuclei by bombardment of the instrument material with particles
• Decay of natural radioactive elements within the instrument material

Especially neutrons are problematic because they are often indistinguishable from γ-rays and can produce long-lived radioactive nuclei
• **Passive Shielding**
  Problem: energetic particles interacting with the material of the passive shield will produce more $\gamma$-rays than will be absorbed by the shield.

• **Active Shielding**
  High-density scintillation detectors that detect both $\gamma$-rays and particle radiation are used to reject any events that occur simultaneously in the shield and the central $\gamma$-ray detector (anticoincidence shield).

• **Pulse-shape discrimination**
  – Interaction mechanism of $\gamma$-rays and neutrons with matter are different.
  – Decay time of the photon-creation process within specially-treated organic scintillators is different.

  => Allows suppression of the neutron-induced background.
Imaging Techniques

• On/Off-Technique
  – To make sensitive measurements it is important to subtract the remaining background.
  – Information about the background spectra can be obtained by observing the source and the background region.
  – Drawback: the background region has to be absolutely source free and the background must be stable.

BATSE (Burst And Transient Source Experiment) (CGRO 1991-2000)
• Full-sky monitor for γ-ray bursts.
• Eight thin scintillation modules, each oriented in a different direction.
• Direction of a γ-ray burst deduced from the relative counting rates with an accuracy of 1° to 10°.
• Measure up to 100MeV using the pair production process.
• Earth occultation technique was also successfully applied by BATSE.
Imaging Techniques

- **Occultation Technique**
  - Positional resolution high when the distance between the detector and the occulter is large
  - From the known positions of the detector and the occulter and from the time when the source signal vanishes, one can derive an arc on the sky on which the source must lie
  - Especially the earth is a good occulter for earth-orbiting satellites
Imaging Techniques

- Imaging via Collimators
  - Field of view defined by Collimators
  - Only $\gamma$-rays with paths more or less parallel to the tube walls can reach the detector

OSSE (Oriented Scintillation Spectrometer Experiment) (CGRO 1991-2000)
- 4 identical detector systems allow the observation of secondary targets and the application of the on/off technique.
- Background suppression through anticoincidence shielding
- Sensitive to $\gamma$-rays in the 0.05-10MeV range and a typical energy resolution of 5-10% depending on energy
Imaging Techniques

- Imaging via Temporal Modulation
  - Path from the source to the detector is intercepted by moving an occulter across the field of view
  - From the positions of the detector and the occulter and from the time when the source signal vanishes one can gain information about the arrival direction of the incident radiation
  - A special variant of the temporal modulation is the Fourier-transform imaging technique

- Compton polarimeter based on a Fourier-transform technique
- Broad energy range of 3 keV to 20 MeV
- High-resolution spectroscopy is achieved with cooled germanium crystals
- Finest angular and spectral resolution of any hard x-ray or γ-ray instrument ever flown in space
Imaging Techniques

- Imaging via Spatial Modulation (Coded Mask)
  - A occulter consisting of opaque and transparent elements arranged in a regular pattern and covering the field of view is called a coded mask.
  - Imaging through such a mask is called the coded-aperture imaging technique.
  - From the measured pattern of the shadow one can reconstruct the position of the point source.

SPI: Specrometer on INTEGRAL
INTEGRAL
INTErnational Gamma-Ray Astrophysics Laboratory

- Launched 2002
- Combined active and passive shielding
- Harbors 2 similar γ-ray telescopes, IBIS and SPI both using coded-masks
- Energy range between 15keV and 10MeV with a resolution of 2keV
- OMC (optical telescope) and JEM-X (x-ray telescope) also on board
  ⇒ Multi-wavelength observations by 4 telescopes

IBIS – Imager
(15 keV – 10 MeV)
Pointsources, Spectra

SPI  (20 keV – 8 MeV)
High-resolution spectroscopy Imaging of sources and diffuse emission

Jem-X  (3-35 keV)

OMC (500 nm)
SPI - Inner Galaxy Deep Exposure

18-143 keV

143-268 keV

268-393 keV

393-518 keV

508-514 keV

e+-e- annihilation line
Compton Gamma Ray Observatory
1991 - 2000

BATSE, OSSE, COMPTEL, EGRET
Comptel
Compton Telescope

- Energy range from ~700keV to ~30MeV
- Charged-particle background suppressed by active shielding, a time-of-flight measurement and a distinction between neutrons and $\gamma$-rays
- Effective area: ~10cm$^2$ to ~50cm$^2$
  (depending on the event-selection criteria and energy)
Comptel
Compton Telescope

$1 - 30 \text{ MeV}$
EGRET
Energetic Gamma Ray Experiment Telescope

- Pair-tracking telescope with a sensitive to γ-rays in the energy range 20MeV to 30GeV
- Field of view of ~1.5sr
- Energy resolution of 20-25%. Its angular resolution improves from ~10° at 60MeV to ~0.5° at 10GeV.
Future Spaceborne Experiments

![Graph showing energy vs. sensitivity for various experiments](image)
MAX

- Below a few MeV present concepts allow for higher sensitivity and better angular resolution only by enlarging the detector area and therefore the size of the instruments
- BUT: Enlargement leads only to small increase in sensitivity, but also to a higher internal background
- Solution: Separation of the collection area and detection volume
- Realized by γ-ray lenses, which utilize crystal diffraction to collect the γ-rays at the focal point

MAX (launch would be ~2011)
- 2 or 3 energy bands
- ~100m focal length starts to require formation flying
- Field of View: ~45 arcseconds

Laue Lens Telescope
GLAST
Gamma Ray Large Area Space Telescope

- Pair-tracking telescope in the energy band from 10 MeV to more than 100 GeV
- Follows in the footsteps of the EGRET experiment
- Field of view about twice as wide and sensitivity more than about 50 times that of EGRET
- The launch of GLAST is anticipated in 2007.
GLAST
Gamma Ray Large Area Space Telescope
EGRET
Energetic Gamma Ray Experiment Telescope

EGRET
Himmelskarte E > 100 MeV
Phase 1 - 4

Cygnus Region
PSR 1951+32
0235+164
3C454.3
2230+114
PSR 1706-44
0208-512
LCM
0537-441

Orion Region
Vela
0446+112
0528+134
PSR1055-52
Geminga
Crab
0827+243

3C279
3C273
1633+382
1622-253
1606+105
1510-069
1406-076
ACT
Advanced Compton Telescope

- Follows in the footsteps of the COMPTEL experiment
- Designed for study of the present low sensitive ~1 MeV region
- Modern sensitive γ-ray detectors will improve efficiency by two orders of magnitude
- Position resolution in the detectors of 1mm$^3$ and energy resolution of 1% or better
- Several designs studied as a „Vision-Mission“ circa 2013-2025
Catalog of Gamma-ray Sources
Summary

Scientific Objectives

Production processes

Interaction Processes
  - Photoelectric absorption
  - Compton scattering
  - Pair production
  - Cerenkov light (secondary particles)

Problems of γ-ray-astronomy

Ground based γ-ray-astronomy
  - Atmospheric Cerenkov Telescopes
    - H.E.S.S.
    - MAGIC

Spaceborne γ-ray astronomy
  - Shielding
  - Imaging Techniques
    - BATSE
    - OSSE
    - COMPTEL
    - EGRET
    - RHESSI
    - INTEGRAL

Future γ-ray astronomy
  - MAX
  - GLAST
  - ACT

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- A Universe in Gamma-Rays (Volker Schönfelder)
- Gamma-Ray Astrophysics (Carl E. Fichtel and Jacob I. Trombka)
- Imaging in High Energy Astronomy (L. Bassini and G. di Cocco)