Observational High-Energy Astrophysics

(5) Radiation and Particle Background

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Overview

• Radiation and particle background
  – Physical processes
  – Impact on instrument design
Background Noise and Sensitivity

• Background radiation (photons and particles) can be considered as “radiation noise” impacting the quality of the measurement and sensitivity.

• A reliable knowledge of the background noise level is fundamental to the estimate of the sensitivity of the instrument.

• The total measured signal is always radiation from source S + background B.

• For gamma-rays: background “noise” is always the dominating component in the measured total (=source + background) signal and must be fully understood in detail.

• At sensitivity threshold, gamma-ray telescopes usually operate at the signal to noise ratio of $S/N \sim 1\%$ (!), so $B(E) \gg S(E)$.

$$F_{\text{Min}}(E, \Theta, \Phi) = \frac{n\sqrt{S(E) + B(E)}}{A_{\text{eff}}(E, \Theta, \Phi) \cdot T_{\text{obs}}}$$
• Determination of the expected background noise and sensitivity, with sufficient accuracy (!) is of **utmost** importance during the design of gamma-ray instruments, and usually follows three approaches:

  – Advanced modeling (“Monte-Carlo”) -> the mass model

  – Particle beam tests for hadronic (protons, neutrons) components

  – Access to in-flight data of previous space missions
Annexe: Monte Carlo

- Monte Carlo methods: computational algorithms that rely on repeated random sampling of a (physical) process to obtain numerical results.
- Used in: optimization, numerical integration, risk assessment, and generating draws from a probability distribution.

> Modeling phenomena with significant uncertainty in input parameters.

- **Example:** With mass $m$, and acceleration $a$ precisely known (“measured”), the force $F = m \cdot a$ can be calculated in a straightforward way. But, both empirical parameters $m$ and $a$ are in fact observables having a probability distribution (e.g. Gauss function), hence $F$ should be determined by combining all probabilities of the range of input parameters for both, $m$ and $a$.

- Monte Carlo methods are often applied in calculating background characteristics of high-energy instruments taking efficiencies, scatter probabilities, decay times etc. including their probability distributions into account.
Annexe: Monte Carlo

Popular example: Calculate $\pi$ via MC simulation
[textbook $\pi = 3.14159265359...$]

1. Draw circle of radius $r$ within a square
2. Area square $S = 4r^2$
3. Area circle $C = \pi r^2$
4. Distribute random points (e.g. rain drops, equal probability) over area $S$
5. Probability $P$ that points are within $C$ is $P = \pi r^2 / 4r^2$, $P = \pi / 4$, hence $\pi = 4P = 4C/S$
6. Create random numbers (here: co-ordinates $[x,y]$) for the points (rain drops) falling uniformly on area $S$ (= # total points) and check whether they also fall within the area $C$ (i.e. condition is: $x^2 + y^2 \leq r^2$)
   - Distribution of points must be uniform, else poor simulation
   - Accuracy of result improves with large($r$) number of points
7. From the number of draws (see 2.,3.) : $\pi = C'/r^2 = 4C'/S'$ ($C'$, $S'$ = # points in C, S)
Popular example: Calculate π via MC simulation
[textbook π = 3.14159265359...]

650 points, π = 4 • C/S = 4 • 504/650 = 3.1015, Δ = 0.0401
1,410 points, π = 3.1234, Δ = 0.0182
5,000 points, π = 3.1504, Δ = -0.0088
50,000 points, π = 3.1469, Δ = -0.0053
1,000,000 points, π = 3.1416, Δ = -0.0000073...

See animation of this example in
https://www.youtube.com/watch?v=VJTFlqO4TU
(if we have WLAN here...)
Background Noise and Sensitivity

1) Detection Efficiency
2) Background Noise Contributions and Methods of Suppression
3) Aperture Flux
4) Shield Leakage
5) Beta Decays and Induced Radioactivity
6) Elastic Neutron Scattering
Background Noise and Sensitivity

1) Detection Efficiency

h.e. photons

detector counts
Background Noise and Sensitivity

1) Detection Efficiency

a. Detection Efficiency is detector dependent and describes the energy-dependent conversion factor from photons to counts (< 1.0)
b. Detection efficiency needs to be calculated for the type of detector under consideration (e.g. CsI, CdTl, Ge), taking energy thresholds etc. into account
c. Discriminate single-site and multiple-site events
d. Prediction by simulation, verification through calibration measurements
Background Noise and Sensitivity

Monte–Carlo simulation for total and photopeak efficiency in a CsI detector array. “Single”: energy deposit in one CsI crystal. “Multiple”: energy deposits in several CsI crystals.

Detection efficiency describes photon $\rightarrow$ count conversion.

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![Graphs showing detection efficiency vs energy for single, multiple, and aggregate deposits](image-url)

ESA, INTEGRAL Phase A report, Sci(93)1, 1993
2) **Background Noise Contributions and Methods of Suppression**

Background modeling usually takes the following *contributions to the total background spectrum* into account, in addition to mass and geometry of the spacecraft and detector systems:

a) Cosmic diffuse background: total integrated high-energy radiation emitted by all celestial high-energy sources, i.e. binaries, AGN, ....)

b) Atmospheric gamma-rays: gamma-rays scattered off Earth atmosphere atoms, molecules, electrons....

c) Gamma-ray photons produced in ambient spacecraft (material)

d) Spallation products induced by cosmic-rays within the material of the detector itself

e) Interactions within the detector involving neutrons (created locally, or from the Earth albedo)

f) Events derived from protons trapped within the van Allen belts
2) Background Noise Contributions

a) Cosmic diffuse background
b) Atmospheric gamma-rays
c) Photons produced in spacecraft
d) CR-spallation products within detector
e) Local or Earth Albedo neutrons
f) Protons within the van Allen belts
3) Aperture Flux

a) Aperture flux is “astronomical radiation”, namely the total integrated cosmic diffuse gamma-ray flux.

b) Aperture flux enters the forward aperture of the instrument.

c) Spectrum is very steep ($\sim E^{-2.3}$), hence at lower energies ($< 300$ keV) the aperture (solid opening angle) needs to be smaller ($\sim$ few deg) than at higher energies ($> 300$ keV, $\sim \pi$ sr).

d) Careful choice of collimator FOV and material to optimize aperture solid opening angle (this is driven by the science objectives !)
Background Noise and Sensitivity

4) Shield Leakage

Shield leakage (background) produces by gamma-ray photons that penetrate the veto shield (...not generating a veto (anti-coincidence) trigger).

- from cosmic diffuse gamma-rays
- from local gamma-rays, produced by CR interaction and their secondaries in the spacecraft material
5) Beta Decays and Induced Radioactivity

Incident neutrons and protons interact with the nuclei in the detector material ("hadron – induced background").

This interaction creates unstable nuclides, which subsequently decay and emit beta-particles (electrons or positrons) and gamma-rays, therefore producing the unwanted signal.

Decays are **not** prompt, but have half-lives between seconds and years and **cannot** be rejected via a (coincident) veto signal.

Estimate of contribution via modeling, semi-empirical methods and verification using ground tests (calibration campaigns).
Background Noise and Sensitivity

6) Elastic Neutron Scattering

Neutrons that elastically scatter off nuclei in semiconductor detectors (e.g. Ge).

Recoil of (heavier) lattice-atoms produce background signal.

Where do the neutrons come from?

Neutrons are produced by
- CR nuclear reactions inside the instrument,
- the spacecraft, and
- the atmosphere below the spacecraft ("albedo")
Background Noise and Sensitivity

Count rates of total estimated background spectrum for a CsI (scintillation) detector

ESA, INTEGRAL Phase A report, Sci(93)1, 1993
Background Noise and Sensitivity

Count rates of total estimated background spectrum for a Ge (semiconductor) detector

ESA, INTEGRAL Phase A report, Sci(93)1, 1993
Radiation Damage

- Significant problem for crystal/semi-conductor detectors (e.g. Ge) in extended (multi-year) space missions
- High-energy protons and neutrons knock lattice atoms out of position producing local regions of radiation damage, so providing trapping sites for electron/hole pairs
- Radiation damage is manifested via degradation of energy line resolution
- Dependant on solar activity cycle (flares, high solar activity)

- Significant recovery of energy resolution for Ge detectors is possible via annealing of detectors (T ~100°C, Duration ~ days)
- Annealing in space causes great mechanical, thermal and electrical stress on detector system and was considered a very critical procedure, until INTEGRAL showed that annealing is in fact a routine operation
Radiation Damage & Annealing

![Graph showing energy resolution in keV vs. revolution's gap with various labels and equations for different revisions and annealing stages.]

SPI - Integral  Jean-Pierre Roques  CoI Meeting - 19th-20th January 2004

Revolution's gap

Rev 10 to 38 (GeD at 90K)
Rev 44 to 89 (after first annealing - GeD at 85K)
Rev 96 to 131 (after second annealing - GeD at 85K)
Rev 137 to ... (after third annealing - GeD at 85K)
Annealing of INTEGRAL Ge detectors

Nov 2002 - Nov 2015
Impact on Instrument Design

Some general remarks – what are the drivers?

- Good shielding of detector array to achieve maximum sensitivity
- Tradeoff veto thickness (transparency = f(E), internal background): science objectives are the drivers
- Impact on mass and size of detector array (launch costs)
- Tradeoff FOV vs aperture leakage
- Sophisticated on-board electronics (e.g. PSD techniques)
- Ge detectors: Thermal control (80K), Annealing capabilities (100° C),
Impact on Instrument Design

In lesson 4, the sensitivity of gamma-ray telescopes is described by

\[ F_{\text{Min}}(E, \Theta, \Phi) = \frac{n\sqrt{B(E)}}{A_{\text{eff}}(E, \Theta, \Phi) \cdot T_{\text{obs}}} \]

with \( n = \# \) standard deviations, \( B(E) = \) background counts \( \gg S(E) \), \( A_{\text{eff}} = \) effective detector area and \( T_{\text{obs}} = \) observing time.

If \( \frac{dF_B}{dE} \) describes the energy spectrum of the background radiation (in units of \( \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{MeV}^{-1} \)), \( \Delta E \) the energy resolution of the detector (FWHM) or any other energy interval used to determine the flux, and \( \Delta \Omega \) is the angular resolution, then the number of background counts is given by:

\[ B(E) = \frac{dF_B(E)}{dE} \cdot \Delta E \cdot \Delta \Omega \cdot A_{\text{eff}}(E) \cdot T_{\text{obs}} \]
Inserting $B(E)$ into $F_{\text{min}}$ gives:

$$F_{\text{Min}}(E, \Theta, \Phi) = n \sqrt{ \frac{dF_B(E)}{dE} \cdot \Delta E \cdot \Delta \Omega \cdot A_{\text{eff}}(E, \Theta, \Phi) \cdot T_{\text{obs}}}$$

- Background flux $dF_B/dE$ has to be as small as possible
  - But the external background is given, so, the internal background must be small !!

- High energy resolution (small $\Delta E$) = higher sensitivity for narrow energy bins

- Maximize $A_{\text{eff}}$ (But: size, mass, cost, power, thermal, complexity)

- Maximize $T_{\text{obs}}$

- Good knowledge of shape of background spectrum $dF_B/dE$
Impact on Instrument Design

How do we know the **shape** of the background spectrum $dF_B/dE$?

1. **Chopper technique**
Supress source signal by blocking the field of view with a “blocking device”, i.e. sufficient thick to block source photons in FOV → **measure background only**. Without “device” → **measure source + background**.

Disadvantages of a “blocking device”:

a) in block/open mode at different locations wrt FOV: different background

b) is itself a source of background photons (created internally)

PS: coded mask measures source + background (mask holes), and background only (blocked mask elements)
Impact on Instrument Design

How do we know the shape of the background spectrum $dF_B/dE$?

2. The On/Off technique
Observe two regions of the sky, for background e.g. regions far off the galactic plane, or near the ecliptic poles.

Disadvantage:
• not entirely source free (e.g. integrated AGN flux for high sensitivity telescopes);
• background measurement requires high stability (no variation with time and direction). Orbital background must be stable!
Background observations

INTEGRAL SPI background time variations.

“end of revolution” = within/near the van Allen belts

Background observations

INTEGRAL SPI background before and at maximum of solar flare of 9 Nov 2002

Background suppression techniques

1. **Passive background suppression**
   Passive shielding using heavy (high-Z) materials as lead (Pb), tungsten (W) with efficient gamma-ray absorption:

   5 cm Pb absorbs ~92% @ 3.5 MeV (minimum) which could be used to build a low background telescope easily using a passive Pb collimator (in the lab....)

   But, in real life, high-energy CR particles impinge on the telescope material inducing gamma-rays inside the collimator via nuclear reactions.

   These (intrinsic background) photons counteract the shielding effect of the collimator.

   **Passive collimation is therefore rather useless in space (for gamma-rays)**
2. **Active background suppression**

Use thin plastic scintillators to suppress charged-particle background, but for high stopping power, one needs about 30 cm thick plastic scintillators to stop 90% of 1 MeV photons. → So, use scintillators such as CsI, NaI, BGO ($\rho = 7.13$ gcm$^{-3}$ !)

What about gamma-rays and neutrons, which can’t be rejected/distinguished by active veto systems?
2. **Active background suppression (cont’d)**

- **Gamma-rays** react via electro-magnetic processes within scintillator (electrons $\rightarrow$ scintillation process)
- **Neutrons** react via nuclear reactions within scintillator (protons $\rightarrow$ scintillation process)

Because electrons and protons have different masses, the decay time of the process creating scintillation photons in the crystal is different for electrons and protons.

This difference of light-decay time can be measured electronically.

$\rightarrow$ Discrimination of neutron-induced scintillation from photon-induced scintillation on-board via measurement of the pulse shape: PSD (pulse shape discrimination)
Background suppression techniques

The active veto BGO system significantly reduces the instrumental background (INTEGRAL/SPI).

Background spectra of Ge events that did not coincide with a trigger of the veto.

Background spectra of Ge events that did coincide (“vetoed only”) with a trigger of the veto (rejected onboard).

The total rate in the 20 keV–8000 keV range changes by a factor $\sim 25$ between both configurations.

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