# Simulation of HEAO 3 Background

B. L. Graham*, B. F. Phlips†,
R. A. Kroeger‡, and J. D. Kurfess‡

*George Mason University, Fairfax, VA
† USRA, Washington, DC
‡ Naval Research Laboratory, Washington, DC

**Abstract.** A Monte Carlo technique for modeling background in space-based gamma-ray telescopes has been developed. The major background components included in this modeling technique are the diffuse cosmic gamma-ray flux, the Earth's atmospheric flux, and decay of nuclei produced by spallation of cosmic rays, trapped protons and their secondaries, the decay of nuclei produced by neutron capture, and the de-excitation of excited states produced by inelastic scattering of neutrons. The method for calculating the nuclear activation and decay component of the background combines the low Earth orbit proton and neutron spectra, the spallation cross sections from Alice91 [2], nuclear decay data from the National Nuclear Data Center's (NNDC) Evaluated Nuclear Structure Data File (ENSDF) database [3], and three-dimensional gamma-ray and beta transport with Electron Gamma-ray Shower version 4 (EGS4) [4] using MORSE combinatorial geometry. This Monte Carlo code handles the following decay types: electron capture, $\beta^-$, $\beta^+$, meta-stable isotope and short lived intermediate states, and isotopes that have branchings to both $\beta^-$ and $\beta^+$. Actual background from the HEAO 3 space instrument are used to validate the code.

## INTRODUCTION

Calculations of the radioactive background in $\gamma$-ray detectors has been a challenging problem since before the first balloon flight of a $\gamma$-ray detector [1]. Reliable calculation of the background rate is essential for future missions because the sensitivity of a $\gamma$-ray telescope is background limited. A Monte Carlo simulation code has been developed that models the background rate due to the decay of spallation products in space based $\gamma$-ray telescopes. The measured background for the High Resolution Gamma Ray Spectrometer aboard HEAO 3 was used to validate this code. This model includes the geometry and composition of the instrument, the incident proton and neutron fluxes on the components of the detectors, the cross-sections for spallation, inelastic scattering and capture, the branching ratios in the decay scheme for the unstable spallation products, the half-lives of the unstable spallation products, and the Monte Carlo transport code that propagates $\gamma$-rays and $\beta$s. The Monte Carlo code does not propagate $\alpha$-particles, protons, neutrons or model $\alpha$-decays.

## MODEL

A mass model, which describes the geometry and composition, was made for the components of HEAO 3. HEAO 3 consisted of four Ge co-axial detectors in a CsI anti-coincidence shield. Each of the Ge detectors was 5.4 cm in diameter and 4.5 cm thick. The detectors were held in a thin aluminum cup. These were all contained in an aluminum cryostat. There was an aluminum cold plate between the detectors and a silver cold finger. There also was a stainless steel baseplate (nominally composed of 10% Nickel, 20% Chromium and 70% Iron). The cryostat was surrounded on all sides by a 6.6 cm thick CsI shield, with holes in the upper lid of the shield which collimated the field of view to $\sim 30°$ [5]. The decays of isotopes produced by the neutron and proton activation of Ge, Al, CsI, Steel and Ag were modeled. Components of the spacecraft outside the shield were not included in the mass model for this work.

The activation of the detectors and surrounding materials was due to a flux mostly composed of secondary neutrons and protons produced by cosmic rays and trapped protons incident on the spacecraft. In this work, the neutron and proton flux used was calculated for an orbit of 500 km at an inclination of 44° [5]. The proton and neutron flux used was scaled according to the scaling method used by Gehrels [6] which was based on data from the balloon instrument, Low Energy Gamma-ray Spectrometer (LEGS) [7].

## SIMULATION

The cross-sections for spallation from neutrons and protons incident on the detectors, shields and support structures were taken from Alice91 [2]. These cross-sections and the neutron and proton flux were evaluated over the energy range of 1 to 250 MeV, thus primary cosmic-ray protons ($>$ few GeV) are not included in this model. The reported errors on the Alice91 spallation cross-sections was less than 30%. The NNDC's Evaluated Nuclear Data File (ENDF) database contains measured cross-sections for neutron capture and inelastic scattering of neutrons to excited states. The model used the $\gamma$-ray spectrum from the Earth's atmosphere as measured by the Solar Maximum Mission (SMM) [8]. This spectrum was folded through both the open collimator response and the response to shield leakage. A $^{40}$K calibration source was modeled inside the cryostat and was fitted to the measured data only at the 1.46 MeV line. The cosmic diffuse $\gamma$-ray background was from the HEAO 1 A4

[9]. This flux is also folded through the open collimator response and the response to shield leakage. The ENSDF database was used for $\beta$ branchings and half-lives for $\beta$-unstable isotopes, and for energy levels and gamma-ray branching ratios for decay products, as well as the half-lives of intermediate states of decay products ($> 1\mu$s). Also included in NNDC databases were the x-ray fluorescence yields and energies of the characteristic x-ray(s) for each isotope [3].

EGS4 is a Monte Carlo transport code that was used for $\beta$ and $\gamma$ transport [4]. Included in EGS4 are routines for the following photon interactions: photo-electric absorption; Compton scattering and pair production, as well as routines for the scattering of electrons; ionization energy losses; Moller, Mott and Bhabha scattering. The combinatorial geometry package MORSE-CG was used, allowing for full three-dimensional propagation of $\beta$s and $\gamma$s.

A routine was designed and implemented for initializing EGS4 to model a nuclear decay, one decay at a time. The $\beta$s and $\gamma$-rays produced for a given isotope in a single decay follow a single series of branchings in a cascade to the ground state of the decay product for each decay modeled via Monte Carlo. This cascade is produced starting from the $\beta$-unstable spallation product isotope and ends at the ground state of the decay product. At the $\beta$-unstable spallation product a $\beta$ branch or Electron Capture (EC) energy or Internal Transition (IT) is chosen from the branchings available (or appropriate) for that spallation product isotope via Monte Carlo selection from the branching ratios. If a $\beta$ branch was selected then the endpoint energy for that branch was used to determine the energy of the $\beta$ from the appropriate $\beta$-spectrum [11,12]. Then the $\beta$ endpoint energy, or the EC energy, was subtracted from the $\Delta$Q value for the decay of this $\beta$ unstable spallation product to determine the energy level of the decay product for the start of the $\gamma$-ray cascade. At each energy level of the decay product a $\gamma$-ray was randomly selected from the possible $\gamma$-rays for that energy level according to their branching ratios. The next energy level was determined by subtracting the energy of the $\gamma$-ray selected from the value of the previous energy level until the ground state of the decay product is reached.

For each $\beta$-unstable isotope that was a spallation product, a number of decays were modeled. For every decay the energy deposited by each interaction in the detectors or the shield was summed for each detector and the shield. The energy resolution was applied to the summed energy for each active element. Then a histogram was made of all decays of a spallation product where the energy deposited in the detector was above the detector threshold, and the energy deposited in the shield was below the shield's threshold. These histograms were summed together with appropriate normalization for the decay rate of each isotope and summed with the cosmic diffuse $\gamma$-ray flux and the Earth's atmospheric $\gamma$-ray flux, and elastic neutron flux and was compared to the measured background rate.

The production rate for each $\beta$-unstable isotope $j$ is

$$R_{prod_j} = \sum_i \int F_n(E)\sigma_{n_{j,i}}(E)a_i\rho_i\frac{N_o}{A_i}VdE + \sum_i \int F_p(E)\sigma_{p_{j,i}}(E)a_i\rho_i\frac{N_o}{A_i}VdE \quad (1)$$

where $i$ is a stable isotope in volume V, $a_i$ is its fractional abundance, $\rho_i$ the density, $N_o$ is Avogadro's number, $A_i$ is the atomic weight, $\sigma_{n_{j,i}}$ and $\sigma_{p_{j,i}}$ are the cross-sections for neutron and proton spallation to $\beta$-unstable isotope $j$ from isotope $i$, and $F_p$ and $F_n$ is the cosmic-ray proton and neutron flux [7]. The fractional abundance $a_i$ was calculated for the isotopic fraction for each element in each material.

A daily South Atlantic Anomaly (SAA) exposure of 220 minutes per day was used. An assumption of 10 SAA passages per day was used resulting in an average of 22.0 minutes for each SAA passage. The detectors on HEAO 3 were turned on starting from 600 s after an SAA passage until the beginning of the next SAA passage.

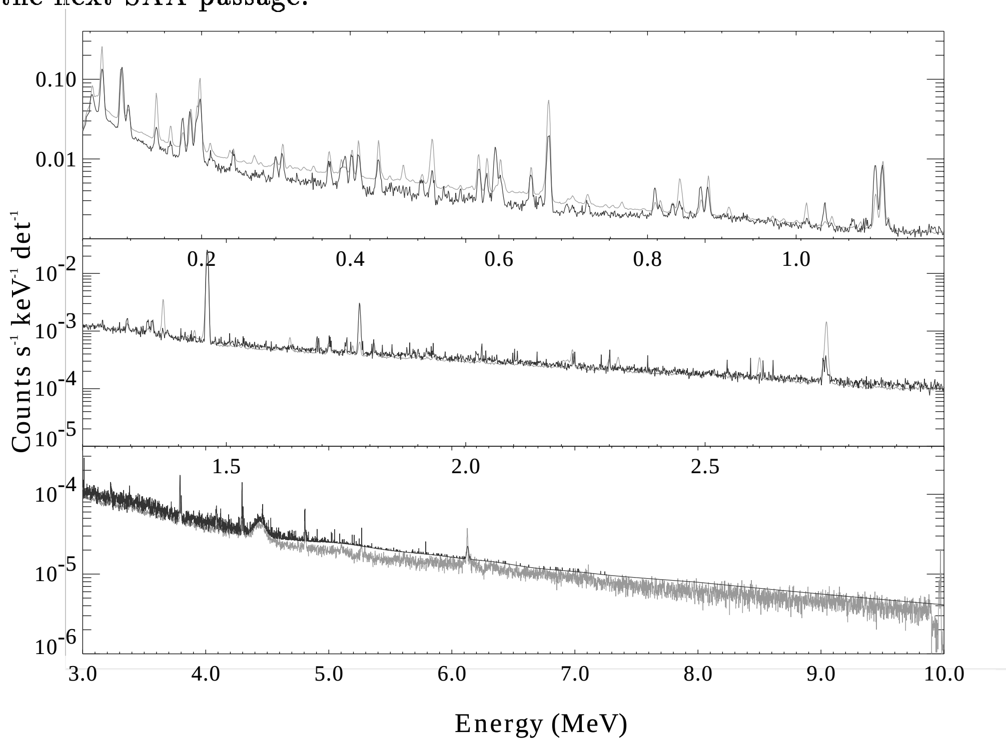


**FIGURE 1.** The sum of all components included in this model (gray curve) versus the measured background rate from HEAO 3 (black curve)

Figure 1 shows the background spectrum modeled for HEAO 3 summed over all components and compared to the measured data taken from the first 50 days of operation [5,10]. Included in the model were all unstable isotopes with production >0.01% of the most abundantly produced from Ge (56 isotopes), all unstable isotopes with production >1.0% of the most abundantly produced from Al (11 isotopes), steel (33 isotopes), CsI (36 isotopes), and Ag (19 isotopes).

## CONCLUSIONS

The Monte Carlo model for HEAO 3 captures most of the major line features and shape of the continuum background. Agreement is good throughout the background spectrum suggesting that the essential physics is being modeled correctly. In the continuum, the data and model agree to within 45% of each other. The difference can be partially attributed to the errors of $\sim$30% in the spallation cross-sections in Alice91 and to the uncertainties in the proton and neutron flux. There are 133 lines observed in the data from HEAO 3. Forty-seven of these lines are not observed in the model, of which 15 are from Bi, U, Pb, Tl and Th contaminates (not modeled) and 7 lines in the HEAO 3 data that were not identified [10]. There are no lines in the model that are not also found in the data within the statistics of comparision. Eighty-six lines are observed in the model that agree with lines in the data. Most of the lines not apparent in the model are weak lines, thus may be absent due to limited statistics.

The HEAO 3 simulation has been used to validate the Monte Carlo Model. With a few minor exceptions that are still being investigated, the model performs well. The future plans for this model is to apply this model to more complicated instruments such as INTEGRAL and a proposed high resolution Compton telescope.

This work was supported by the Office of Naval Research, ONR, work request # N0001497WX40001, task area # LR0340643.

## REFERENCES

1. L. E. Peterson *J. Geophys. Res.* **68**, 979 (1963).
2. Blann and Vonach, *Phys. Rev* **28**, 1475 (1983).
3. National Nuclear Data Center (NNDC), Brookhaven National Laboratory, Brookhaven, NY.
4. W.R. Nelson et.al. **SLAC-265** (Stanford University), (1985).
5. W. Mahoney et.al. *NIM* **179**, 363 (1980).
6. N. Gehrels, *NIM A* **313**, 513 (1992).
7. N. Gehrels, *NIM A* **239**, 324 (1985).
8. J. Letaw, et.al. *J. Geophys. Res.* **94**, 1221 (1989).
9. L. E. Peterson private communication.
10. W. Wheaton et.al. *High Energy Radiation Background in Space*, American Institute of Physics, 304 (1989).
11. K. Seigbahn *Alpha, Beta and Gamma-Ray Spectroscopy*, 1337-1339 (1965).
12. Evans *Atomic Physics*, McGraw-Hill, 548-552 (1955).