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The ACT vision mission study simulation effort

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Abstract

The Advanced Compton Telescope (ACT) has been selected by NASA for a one-year ''vision mission'' study. The study's main goal is to determine feasible instrument configurations to achieve ACT's sensitivity requirements, and to give recommendations for technology development. Space-based instruments operating in the energy range of nuclear lines are subject to complex backgrounds generated by cosmic rays, earth albedo radiations, trapped particles, and diffuse gamma rays; typically measurements are significantly background-dominated. Therefore accurate, detailed simulations of the background induced in different ACT configurations, and exploration of event selection and reconstruction techniques for reducing these backgrounds, are crucial to determining the capabilities of a given instrument configuration. The ACT simulation team has assembled a complete suite of tools that allows the generation of particle backgrounds for a given orbit, their propagation through any instrument and spacecraft geometry – including delayed photon emission from instrument activation – as well as the selection and reconstruction of Compton events in the given detectors. We describe here the scope of the ACT simulation effort and the suite of tools used.

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1. Introduction

An Advanced Compton Telescope (ACT) has been regarded as the next step for γ-ray astronomy in the nuclear-line energy regime for about a decade (NASA GRAPWG, 1997, 1999). It is expected to provide roughly two orders of magnitude in sensitivity improvement over existing MeV instrumentation (Boggs et al., 2005). ACT has been undergoing a NASA ''vision mission'' concept study for the past year, with the simulation effort described here constituting the core of the study.

The goal of the simulation effort is to derive realistic performance estimates for ACT. Space-based instruments operating in the energy range of nuclear lines are subject to complex backgrounds generated by cosmic rays, earth albedo radiations, trapped particles, and diffuse γ-rays. The count rate from this background typically far exceeds that from astrophysical γ-ray sources. Maximizing the signal and minimizing the background depends critically on complex event selection and reconstruction algorithms, which in turn depend on the exact geometry of the instrument. Detailed computer simulations allow us to efficiently explore this vast parameter space and are thus vital for optimizing the instrument design and predicting its performance. For the ACT simulation effort, we have combined existing tools into a complete, powerful package for γ-ray astronomy.

2. Tools and their heritage

2.1. MGGPOD

MGGPOD (Weidenspointner et al., 2005) is a suite of Monte Carlo codes built around the GEANT3.21 package (CERN, 1993) to simulate *ab initio* the physical processes relevant for the production of instrumental backgrounds at γ-ray energies. These include the build-up and delayed decay of radioactive isotopes as well as the prompt de-excitation of nuclei, both of which give rise to a plethora of instrumental γ-ray background lines in addition to continuum backgrounds. The MGGPOD package has been successfully applied to modeling the instrumental backgrounds of the TGRS (Weidenspointner et al., 2005), SPI (Weidenspointner et al., 2003), and RHESSI (Wunderer et al., 2004) instruments. To illustrate the performance of MGGPOD, we depict both simulated and measured instrument backgrounds for TGRS in Fig. 1. For the ACT simulations, additional input particle geometries – intensity

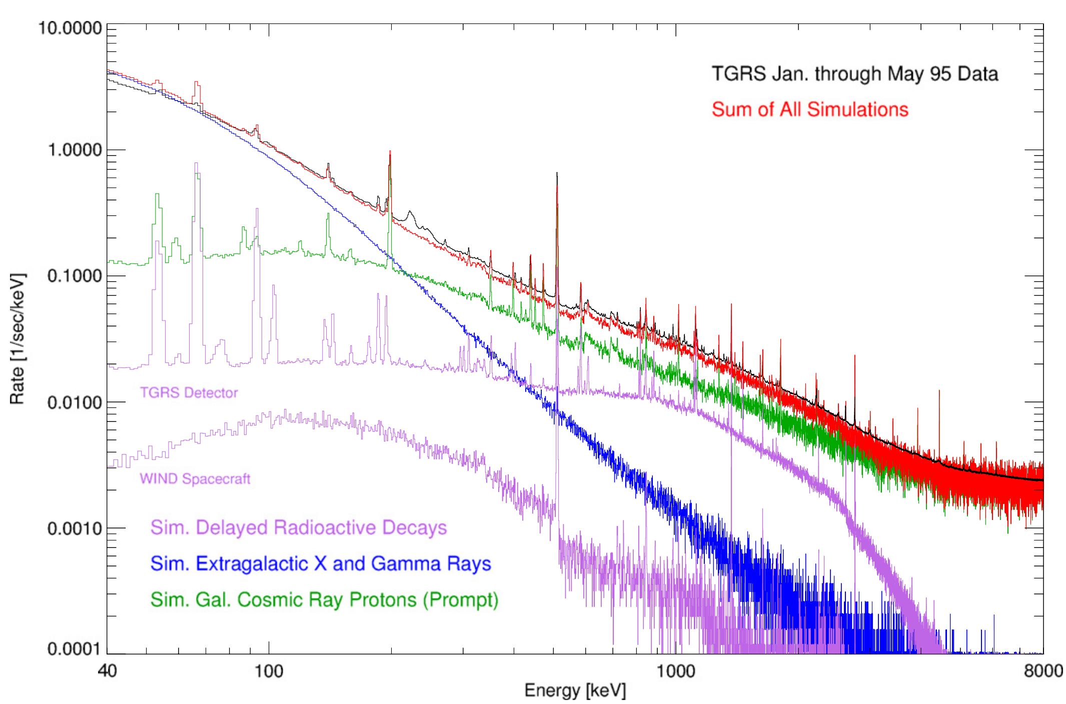

Fig. 1. MGGPOD-predicted and measured in-flight backgrounds for TGRS (from Weidenspointner et al. (2005)).

distributions that vary as a (tabulated) function of azimuth angle in addition to the existing beam and isotropic geometries –, neutron cross-sections, and more detailed event output had to be added to the package while the core simulation code remained unchanged. MGGPOD also includes the GLECS (Kippen, 2004) and GLEPS (McConnell et al., in preparation) packages for simulating the effects of atomic binding and polarization on photon scattering processes.

2.2. Environment model

The MGGPOD package depends on accurate space environment model inputs for reliable prediction of the induced instrument background. For ACT, we have generated a tool capable of producing background component input spectra in MGGPOD format based on the CREME96[1] package. CREME96 is widely used to give dose predictions for determining satellite electronics design constraints and has been shown to be accurate at predicting galactic cosmic ray, anomalous cosmic ray, and solar flare components of the near-earth environment (Tylka et al., 1997). The package also includes a well-tested geomagnetic transmission calculation algorithm, and uses the established AP8 models for predicting trapped proton flux. For the atmospheric neutron environment component, the models based on empirical data reported in Morris et al. (1995, and references therein) are used. For the electron/positron cosmic rays, the diffuse photon and the albedo photon components, the analytical models presented by Mizuno et al. (2004) are used convolved with the geomagnetic transmission function supplied by CREME96. The electron cosmic rays are extended to energies below 7 GeV based on data provided in Ferreira (2002).

2.3. MEGALIB

The MEGAlib package (Zoglauer, these proceedings) was originally developed for the MEGA prototype, a Compton telescope consisting of a thin Si tracker (a detector consisting of Si-strip detectors thin enough to enable recoil electron tracking in the Compton regime) and a CsI calorimeter. The package contains the complete data analysis chain for Compton telescopes, from discretizing simulation data and calibrating real measurements to the reconstruction and selection of events, up to high-level data analysis, i.e., image reconstruction, background estimation, and polarization analysis. For the ACT study, the package has been enhanced to include reconstruction of incompletely absorbed events with four or more interactions (relevant in particular to a thick-Si instrument), time-of-flight information, background due to random coincidences, and more.

[1] http://creme96.nrl.navy.mil/.

The most critical part in the data analysis is the event reconstruction, because it has to extract the source events from the background events. Different approaches are implemented or under development. The most promising technique is based on Bayesian statistics.

The end-to-end capabilities of MEGAlib are illustrated in Fig. 2 for an extended, ring-shaped source observed by MEGA in the laboratory.

2.4. ACT mass model

To model different detector concepts, we need to be able to easily modify detector materials and geometries – including structural materials – while the problem of background lines from satellite activation forces us to include a fair level of detail even in rough-estimate mass models. We have built a universal ACT mass model generation tool that easily supports different detector and structural materials and combines them with a somewhat generic spacecraft model (based loosely on GLAST). This tool also facilitates the comparative performance simulations for different instrument concepts. Figs. 3 and 4 show the baseline-ACT mass model consisting of Si and Ge layers

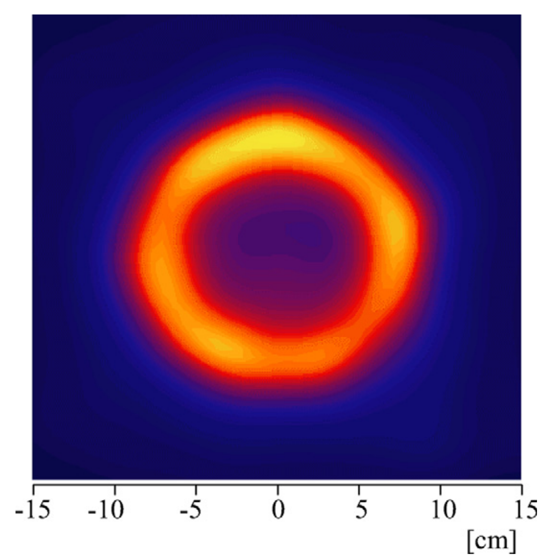

Fig. 2. MEGAlib-based reconstruction of an extended (ring-shaped) laboratory source using MEGA prototype data. For details see Zoglauer (2005).

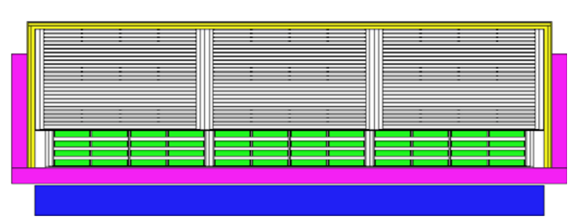

Fig. 3. The ACT Si–Ge baseline instrument mass model: Si (gray) and Ge (green) layers surrounded by plastic (yellow) and BGO (pink) anticoincidence shields. (For interpretation of the references in colour in this figure legend, the reader is referred to the web version of this article.)

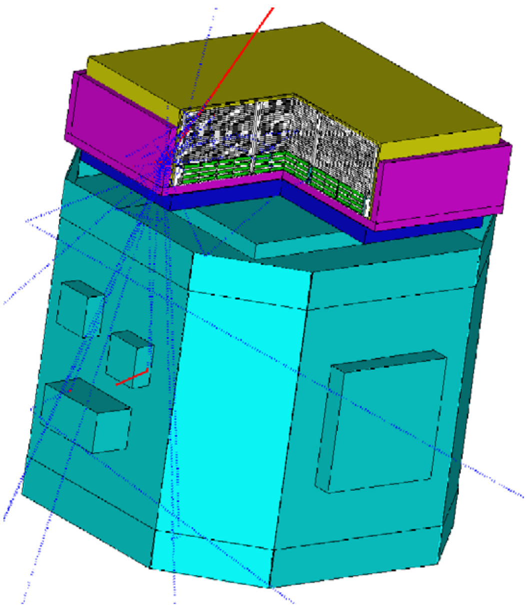

Fig. 4. Image of full ACT spacecraft mass model for the Si–Ge baseline instrument. Simulated secondary particles resulting from an incident energetic electron are shown.

surrounded by plastic and BGO anticoincidence shields with the generic spacecraft.

The mass model generation tool organizes the detectors in stacks and layers, with several stacks combined to form a detector assembly. Each detector's material and dimensions can be specified, as can the thickness and material for space between the detectors, layers, and stacks. The instrument can consist of two different detector assemblies stacked on top of each other (as the Si and Ge detectors in the ACT baseline in Fig. 3). Additional assemblies can be placed at the four sides. The detectors can then be surrounded by particle anticoincidence shields on five (all except bottom) or six sides (plastic in our example), and by a massive anticoincidence shield at the bottom and sides (BGO for the ACT baseline). For the shields again thickness and material as well as surrounding passive materials can be specified.

3. Status

The ACT study is finished – the resulting report has been submitted in December 2005 (Boggs et al., 2005). The ACT simulation pipeline, comprising all the tools and steps discussed above, has been tested and used end-to-end at multiple sites for a host of very different instrument designs relying on a multitude of detector systems. It is reasonably easy to use, and all stages can easily be modified.

We have verified our environment model by comparison with models used for RHESSI and TGRS modeling, as well as through comparison with published literature for the various background components. We have enhanced the quality of neutron cross-sections available in MGGPOD for Ge, Si, and Xe isotopes and established methods to perform the same task for other relevant isotopes (e.g., other detector materials). The event reconstruction methods of MEGAlib, originally geared towards electron tracking telescopes, have been expanded significantly to also handle telescope designs relying on time-of-flight and/or multi-Compton interactions.

We have used this package to optimize and characterize the performance of more than a dozen candidate instrument designs for an Advanced Compton Telescope. Figs. 5 and 6 illustrate the crucial Compton event reconstruction and event selection steps by comparing the instrumental backgrounds (Si–Ge baseline instrument; 550 km altitude, 8° inclination baseline orbit) before and after.

The spectrum in Fig. 5 contains all events with at least two measurable interactions in the detectors and no simultaneous, above-threshold interaction in the anticoincidence

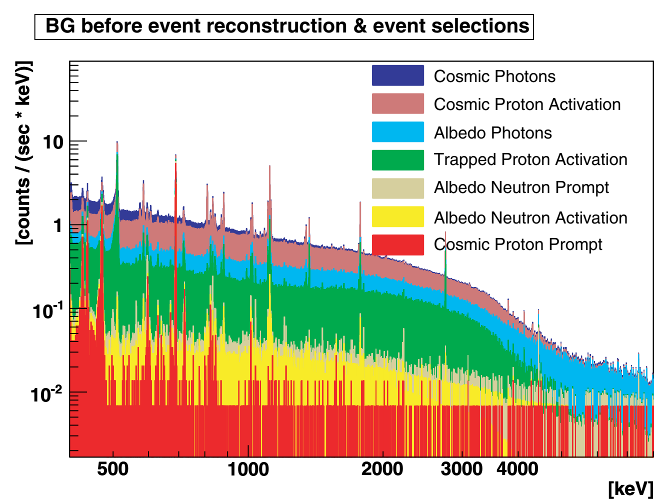

Fig. 5. Background induced in the ACT Si–Ge baseline instrument (cumulative plot of the different components), before event reconstruction or any selections are applied.

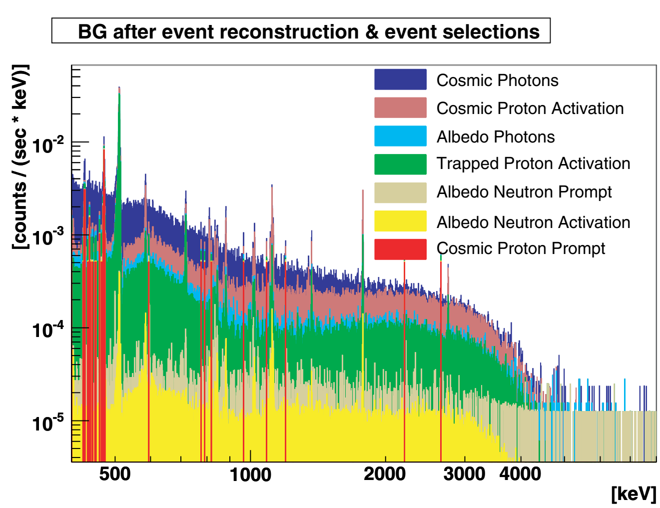

Fig. 6. Background induced in the ACT Si–Ge baseline instrument (cumulative plot of the different components), after event reconstruction and event selections are applied.

shields. The spectrum in Fig. 6 in contrast shows only those events that remain after (Bayesian) event reconstruction and the application of event selections that optimize the instrument's sensitivity to, in this case, an 847 keV 3%-broadened on-axis line source.

Event reconstruction determines if the event is consistent with a (multiply) Compton-scattered photon, yields the incident direction of the photon for any given event, as well as a quality factor encoding how likely the result of the event's reconstruction is correct. Event selections restrict allowed event parameters in order to optimize the instrument sensitivity (i.e., the minimum source flux detectable in 10^6 s at 3σ significance).

For the ACT baseline instrument and a 3%-broadened 847 keV line on-axis source, the selections applied are: energy 830–864 keV, angular deviation from source 0° to 1.1°, Compton scatter angles 0–130°, events with 3–7 interactions, rejection of photons consistent with 90° or less from nadir (earth horizon cut), minimum distance between interactions 1.6 cm, and quality factor 0–0.65.

The event reconstruction combined with these event selections reduces the background rates by three orders of magnitude. The same steps reduce the source photopeak signal by only a factor of 6.8. The resulting sensitivity of the Si–Ge baseline instrument to a 3%-broadened 847 keV line is 1.2×10^{-6} ph cm^{-2} s^{-1} in 10^6 s. Predicted narrow-line sensitivities are, e.g., 5.2×10^{-7} ph cm^{-2} s^{-1} at 847 keV and 4.9×10^{-7} ph cm^{-2} s^{-1} at 1809 keV.

4. Future

We have come a long way – but our work is not done. Further optimizations to the existing package will enhance its capabilities and can make (parts of) it applicable to an even larger community of X- and γ-ray astronomers: detailed neutron cross-sections are still missing for relevant isotopes (e.g., Cd, Zn, Te, La, Br, Cs, I, Al, etc. – for some of these neutron cross-sections are currently being implemented), and GEANT's proton cross-sections must be verified in detail. Bayesian event reconstruction should be implemented for a larger selection of instrument designs, including those relying on time-of-flight or energy reconstruction from multiple Compton events.

Already other mission or study teams (EXIST, NuSTAR, CASTER, MEGA, etc.) have expressed interest in using some of the ACT study tools. A continuation of the community-wide concerted simulation effort begun here constitutes one of the "technology development" recommendations the ACT study team is making to NASA.

Acknowledgement

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