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Background model for a gamma-ray satellite on a low-Earth orbit

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Abstract. The main background components in a low-Earth orbit are charged particles and photons, both primary and secondary, as well as neutrons. A model of these components, based on data from previous instruments, has been developed for energies between 10 keV and 100 GeV. The model dependence on inclination has been studied for a mean solar activity and activation simulations from such a background have been carried out using the model of a possible future gamma-ray mission (e-ASTROGAM). The results from these simulations have been compared with the activation from the passage through the South Atlantic Anomaly (SAA). The primary protons are found to be the main contributor of the activation at 0° while the long-term activation from the passage through the SAA becomes the main source of background for inclinations higher than $\sim$ 10°. The SAA contribution to the 511 keV line background must be always taken into consideration, up to several minutes after the passage for high inclination orbits (i$\gtrsim$ 15°).

Key words. Background – Gamma-ray – satellite – LEO

1. Introduction

All missions suffer from a background, a model of which is necessary both during the planning of a mission and during the data analysis. For a gamma-ray satellite in a low-Earth orbit (LEO) the main components of the background are: primary cosmic rays (protons, electrons, positrons and alpha particles), galactic and extragalactic gamma rays and secondary particles created by the interaction of the cosmic rays with Earth atmosphere. Among these the most important contributors are the albedo photons, atmospheric neutrons and secondary charged particles.

We propose a model of each of these components (Cumani et al. 2019), which we collected in an open repository[1]. The only input necessary to the model are the inclination and altitude of the considered orbit, from which the geomagnetic cutoff value R_{cutoff} is calculated as in Smart & Shea (2005). Every component is modeled starting from experimental data and previously existing models (see Cumani et al. (2019) for a complete description of each component):

[1] https://github.com/pcumani/LEOBackground

- Photons: from SAS 2, as described in Mizuno et al. (2004), the IBIS/ISGRI gamma-ray imager instrument of INTEGRAL (Türler et al. 2010; Sazonov et al. 2007; Churazov et al. 2006), Fermi-LAT (Ackermann et al. 2015; Abdo et al. 2009) and its openly available background model [2].
- Primary charged cosmic rays: from AMS-02 data (Aguilar et al. 2015b,a, 2014).
- Secondary charged cosmic rays: following the equation from Mizuno et al. (2004), describing AMS-01 data (Alcaraz et al. 2000b,a).
- Atmospheric neutrons: two different models (Kole et al. 2015) and (Lingenfelter 1963), down to 0.01 eV.

2. General background

In the following, if not differently specified, all the results are obtained for an equatorial orbit (inclination $i = 0°$) at 550 km and with a medium solar activity. The spectra of all the components in $\mathrm{m^{-2}s^{-1}MeV^{-1}sr^{-1}}$ are shown in Fig. 1.

The dominant photon component is highly dependent from the line of sight of the considered detector. Extragalactic photons are the main contributors below 100 keV, while albedo photons, if part of the atmosphere is in the instrument field of view, are dominant above that energy. Albedo photons are the primary component up to the highest energies, surpassed only for observations close to the Galactic center, at 400 MeV, or Galactic disk, at 1 GeV.

Secondary charged particles, positrons first and protons later, are dominant contributors up to $\sim$ 6 GeV, after which they are surpassed by the primary protons.

The validity boundaries of the model for the different components of the background, mainly related to the limits from the data on which the model is based, are presented in Tab. 1.

[2] https://fermi.gsfc.nasa.gov/ssc/data/access/lat/BackgroundModels.html

3. Activation simulations

While most of the charged particles interaction with the detector are usually vetoed by an anticoincidence system, their interaction with the satellite might create unstable isotopes which, decaying, can create a signal similar to a Compton event. This activation is directly related to the detector geometry and materials. We used the gamma-ray mission proposal e-ASTROGAM (De Angelis et al. 2017), capable of detecting gamma rays between 300 keV and 3 GeV, as a reference instrument for this study. Its main detectors are: a silicon tracker, a calorimeter composed by CsI(Tl) crystals, and a plastic scintillator anticoincidence. Descriptions of spacecraft, electronics, and passive materials were also included in the mass model.

The detector activation (Zoglauer et al. 2008) on orbit with inclination between 0° and 15° was simulated using the Medium Energy Gamma-ray Astronomy library (MEGAlib) toolkit (Zoglauer et al. 2006). The toolkit calculates which isotopes are created after a certain irradiation time in each volume of the detector and their abundance. The irradiation can either be constant during the whole time, or be followed by a certain cool down time, during which there is no irradiation but observation have not yet restarted. Three different type of irradiation were used depending on the considered particle:

- A constant 10 min irradiation with different cool downs (0, 60, 120, 300, 600 s) for the simulation of the short term contribution from the South Atlantic Anomaly (SAA), affecting observation at every orbit. The SAA is the region, which boundaries change with altitude, inclination and energy threshold, where the inner Van Allen radiation belt comes closest to the Earth surface. The AE9/AP9-IRENE Ginet et al. (2013) models (version 1.5, O'Brien et al. 2018) have been used to obtain the spectra of the SAA for the different considered orbits.
- A constant 72 days (equivalent to 1 year of passages) irradiation with a different 45 minutes cool down (half a orbit) for the

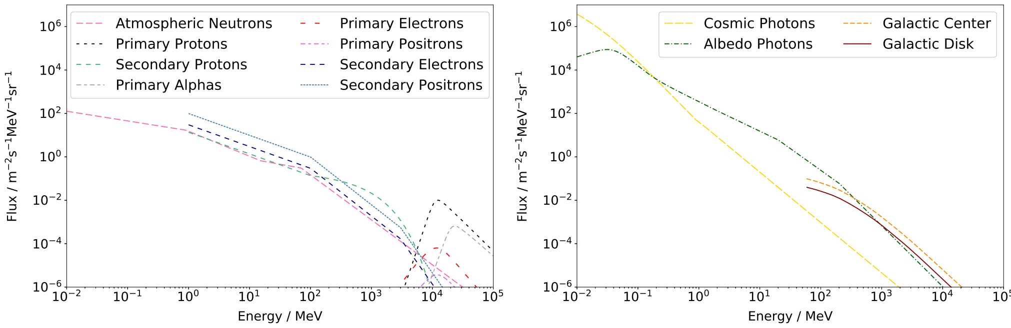

Fig. 1. Full on-orbit background spectrum for charged particles and neutrons (*left*) and photons (*right*). All spectra components shown are divided by the solid angle of their region of origin therefore pointing and field-of-view of an hypothetical instrument are not considered.

Table 1. Validity limits of the different components of the background.

	Orbit Parameters	Energy
Extragalactic γ	Independent	4 keV - 820 GeV
Galactic γ	Independent	58 MeV - ~ 513 GeV
Albedo γ	All LEOs	1 keV - 400 GeV
Primary p	All LEOs	10 MeV - 10 TeV
Primary α	All LEOs	10 MeV - 10 TeV
Primary e$^{\pm}$	All LEOs	570 MeV - 429 GeV
Secondary p	$1.06 \leq R_{cutoff} \leq 12.47$	1 MeV - 10 GeV
Secondary e$^{\pm}$	$1.06 \leq R_{cutoff} \leq 12.47$	1 MeV - 20 GeV
Atmospheric n	$10\ \mathrm{km} \lesssim h \lesssim 1000\ \mathrm{km}$ $i < 65°$	0.01 eV - ~ 30 GeV

simulation of the long term contribution from the SAA.

– A constant 1 year irradiation, without cool down for the primary and secondary protons, alpha particles, and atmospheric neutrons.

The last step is the simulation of the isotopes decay after the irradiation. The isotopes which contributes more to the background are reported in Tab. 2. Most of the decays, especially at long term, are caused by the isotopes abundantly created in the CsI(Tl) crystals of the calorimeter.

3.1. Analysis: count rates and spectra

The rates of events reconstructed as Compton for both the general background and the SAA are shown in Fig. 2. The decays of the isotopes created by the primary protons are the main

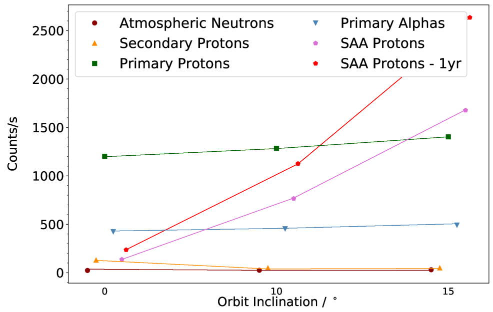

Fig. 2. Comparison of the results of the activation caused by the general on-orbit background and by the passage of the SAA, both from the short-lived isotopes, without considering any cool down time, and from the long-live ones. Results are shown for three different orbit inclinations. All the results were calculated for an altitude of 550 km.

Table 2. List of the most relevant isotopes created by the particles passing through the different e-ASTROGAM volumes. Results are given as relative to the most active source of background, which have a value of 1. The results are generally consistent for all the components, with some exceptions for the atmospheric neutrons (n) and secondary protons (sp).

Isotope	$T_{1/2}$	Activation$_i$ / Activation$_{max}$			Volumes
		General Background	SAA 1 yr	SAA 1 orb.	
^{11}C	20 m	0.2 (0.6 sp)	1	0.8	Anticoincidence Supports Spacecraft Electronics
^{128}I	25 m	1	0.9	0.4	Calorimeter Crystals
^{126}I	13 d	0.3	0.7	< 0.1	
^{132}Cs	6.5 d	0.2	0.8	< 0.1	
^{134}Cs	2.1 yr	0.5	0.3	< 0.1	
^{125}I	59 d	0.2	0.5	< 0.1	
^{131}Cs	9.7 d	0.1	0.5	< 0.1	
^{123}I	13 h	0.1	0.5	< 0.1	
^{122}I	3.6 m	0.1	0.1	0.1	
^{126}Cs	1.6 m	< 0.1	< 0.1	0.1	
^{25}Al	7.2 s	< 0.1 (0.1 sp)	< 0.1	0.5	Spacecraft Electronics Tracker Wafers Calorimeter Diodes
^{28}Al	2.2 m	0.3 (0.4 n)	< 0.1	0.5	Calorimeter Diodes Electronics Tracker Wafers
^{15}O	2 m	0.1 (0.3 sp)	< 0.1	1	Anticoincidence Electronics Supports

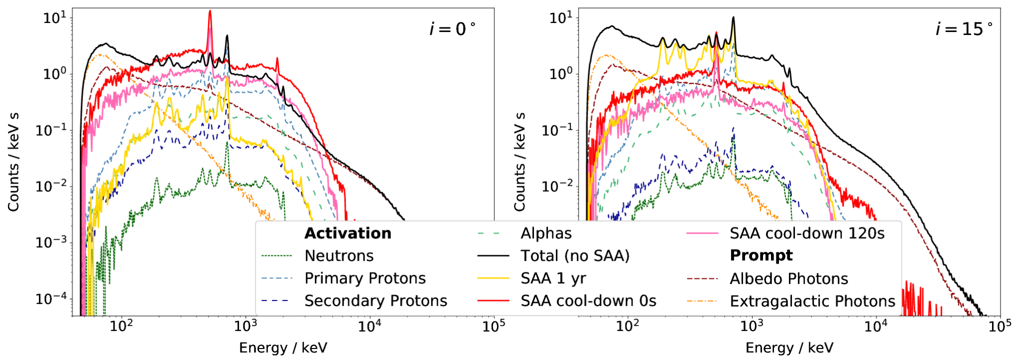

Fig. 3. Spectra of the reconstructed background Compton events for an orbit inclination of 0° (*left*) or 15° (*right*). The total (no SAA) is calculated as the sum of all the component from the activation except the SAA contribution. The SAA contribution is divided in short-term, with a 0 s or 120 s cool down, and long-term (SAA 1 yr).

contributors to the total rates, the alpha particles contribution being a third of that. The rates from neutrons and secondary protons are negligible. The long-term SAA activation contribution is higher than the short-term by a factor $\sim 1.5 - 1.6$ in the considered inclination range. From being negligible for an equatorial orbit, the SAA become the second contributor at 10° and the first at 15°, surpassing the rates from the primary protons by a factor of 1.9.

The spectra of the reconstructed Compton events from the activation simulations and from the extragalactic and albedo photons for two different orbit inclinations are shown in Fig. 3. Without considering the SAA, the main contributors are the photons ($E \lesssim 400$ keV, $E \gtrsim 3$ MeV), and primary protons (400 keV$\lesssim E \lesssim 3$ MeV). The extragalactic photons are the main contributor below 100 keV, but they quickly loses importance at higher energies.

Even though the event rates might be negligible, the SAA effect must always be considered for observations of the 511 keV line. Considering a two minutes cool down the contribution from the short-term SAA drops to a tenth of the summed spectra of all the other components for an equatorial orbit but the two are comparable for an inclination of 15°. At this inclination the long-term SAA activation is higher than the the sum of all the other components between ~ 150 keV and ~ 720 keV. High inclination orbits are therefore disfavoured.

Apart from the 511 keV line, created by the annihilation of positrons from β^+ decay, the other most prominent line is the 700 keV one. This line is mostly generated by the decay of long lived isotopes abundantly created in the CsI(Tl) crystals of the calorimeter. For this reason it is less important for the short-term SAA contribution.

4. Conclusions

Even if shielded by the geomagnetic field, satellites observations in low-Earth orbits are affected by a particle flux dependent on the orbit parameters. A model for this background, based on data from present and past experiments, has been proposed and applied to a possible future gamma-ray mission, e-ASTROGAM (De Angelis et al. 2017), to estimate the satellite activation using the tool MEGAlib (Zoglauer et al. 2006). The results were compared with the activation from the passage through the South Atlantic Anomaly (SAA), the spectrum of which was computed using the AE9/AP9-IRENE (Ginet et al. 2013) model.

The primary cosmic-ray protons are found to be the main contributor of the background, followed by the alpha particles. The neutrons and secondary protons contributions can be considered negligible. The SAA contribution to the total events rate gains importance when increasing the inclination of the orbit: from being negligible in nearly equatorial orbit, it becomes the main contributor at 15°.

The SAA long-term activation spectrum is found to be higher than the sum of all the other components between 150 and 720 keV at 15°, and comparable to the alpha particles spectrum at 0°. The SAA short term contribution to 511 keV line is always important and a long cool down is needed at high inclination.

The orbit with the lowest background has therefore a low inclination ($i < 5$, Cumani et al. 2019)

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References

Abdo, A. A., Ackermann, M., Ajello, M., et al. 2009, Phys. Rev. D, 80, 122004
Ackermann, M., Ajello, M., Albert, A., et al. 2015, ApJ, 799, 86
Aguilar, M., Aisa, D., Alpat, B., et al. 2015a, Phys. Rev. Lett., 115, 211101
Aguilar, M., Aisa, D., Alpat, B., et al. 2015b, Phys. Rev. Lett., 114, 171103
Aguilar, M., Aisa, D., Alvino, A., et al. 2014, Phys. Rev. Lett., 113, 121102
Alcaraz, J., Alpat, B., Ambrosi, G., et al. 2000a, Physics Letters B, 484, 10
Alcaraz, J., Alvisi, D., Alpat, B., et al. 2000b, Physics Letters B, 472, 215
Churazov, E., et al. 2006, arXiv e-prints, arXiv:0608.0608252

Cumani, P., et al. 2019, arXiv e-prints, arXiv:1902.06944
De Angelis, A., Tatischeff, V., Tavani, M., et al. 2017, Experimental Astronomy, 44, 25
Ginet, G. P., O'Brien, T. P., Huston, S. L., et al. 2013, Space Sci. Rev., 179, 579
Kole, M., Pearce, M., & Muñoz Salinas, M. 2015, Astroparticle Physics, 62, 230
Lingenfelter, R. E. 1963, Journal of Geophysical Research, 68, 5633
Mizuno, T., Kamae, T., Godfrey, G., et al. 2004, ApJ, 614, 1113
O'Brien, T. P., Johnston, W. R., Huston, S. L., et al. 2018, IEEE Transactions on Nuclear Science, 65, 462
Sazonov, S., et al. 2007, MNRAS, 377, 1726
Smart, D. & Shea, M. 2005, Advances in Space Research, 36, 2012
Türler, M., Chernyakova, M., Courvoisier, T. J.-L., et al. 2010, A&A, 512, A49
Zoglauer, A., Andritschke, R., & Schopper, F. 2006, New Astronomy Review, 50, 629
Zoglauer, A., et al. 2008, in 2008 IEEE Nuclear Science Symposium Conference Record, 2859