Estimating the Effect of Radiation Belt Passages on SPI's Instrumental Background

Version 2

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1 Introduction

This document provides an update of studies of the effect of radiation belt passages on SPI's instrumental background. Background spectra for various heights of the initial perigee of the INTEGRAL spacecraft orbit are given, as well as background spectra for three so-called contingency orbits.

During radiation belt passages INTEGRAL is exposed to an intense flux of protons of relatively low (compared to primary cosmic rays) energy. These radiation belt protons will result in activation of spacecraft and intrument materials which then decays after the passage. The decay of radiation belt activation represents a time variable contribution to the "baseline" or "quiescent" instrumental background due to primary cosmic-ray particles (including both prompt and delayed components) and diffuse cosmic photons. The quiescent background is independent of the proposed initial perigees and varies on much longer time scales than contributions from radiation belt passages.

These investigations provide guidance for various aspects of INTEGRAL mission planning. The selection of the initial perigee height of INTEGRAL is a trade-off between spacecraft propellant consumption at the beginning of the mission and instrumental background levels, particularly for SPI. The higher the initial perigee the lower the background due to radiation belt passages – and the less fuel is available for orbit corrections later in the mission. Similarly, in case of a failure of the last stage of the PROTON launcher, INTEGRAL will end up in a so-called contingency orbit. The perigee height of such a contingency orbit depends to some degree on the amount of on board fuel spent for orbit adjustments. The more on board fuel is spent to raise the perigee, the less fuel is available for later operations, limiting the duration of the mission. Activation from radiation belt passages is also of interest during the low-Earth orbit phase following launch, during the tuning of the scientific instruments, and during the performance verification phase. Ideally, during these operations any radioactivity due to radiation belt passages is negligible compared to the quiescent background.

2 Radiation Belt Proton Spectra

2.1 Investigating the Effect of the Initial Perigee Height

The data on the radiation belt proton spectra used for this study were provided by A. Parmar, ESA ESTEC. They consist of a time series of spectra for each of four initial perigee heights: 8500 km, 9000 km, 9500 km, and 10,000 km. The time series cover about 170 orbits or the first 1.4 years of the mission. For each of these four initial perigees the orbital evolution results in an increase of the perigee. The effect of the orbital evolution on the proton spectrum is a decrease of the overall flux above about 1 MeV, a softening of the spectrum, and a decrease of the high energy cut-off.

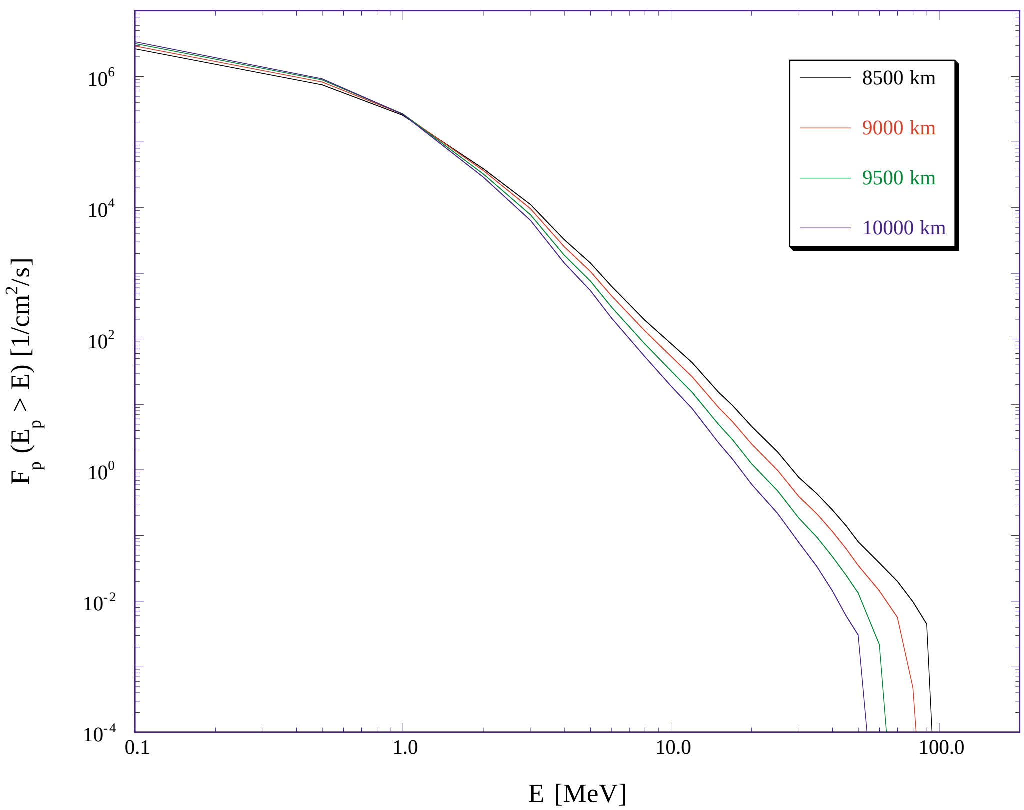


Figure 1: The worst case orbits for each of the four initial perigee heights. Details are given in the text.

For simplicity, the simulations were based on the "worst case" orbit (orbit #6) for each of the four initial perigee heights (see Fig. 1). These are the orbits with the highest proton fluxes, particularly above 10 MeV (only protons with energies above about 10 MeV are expected to significantly contribute to the activation), and at the same time the highest proton energy cut-off. Simulation of the worst case orbits should yield an upper limit on the instrumental background due to radiation belt passages. It has to be noted that the integral fluxes in Fig. 1 represent orbit averaged fluxes derived by dividing the proton fluence by the orbital period (3 days). In the simulations the proton spectra were re-normalized, assuming

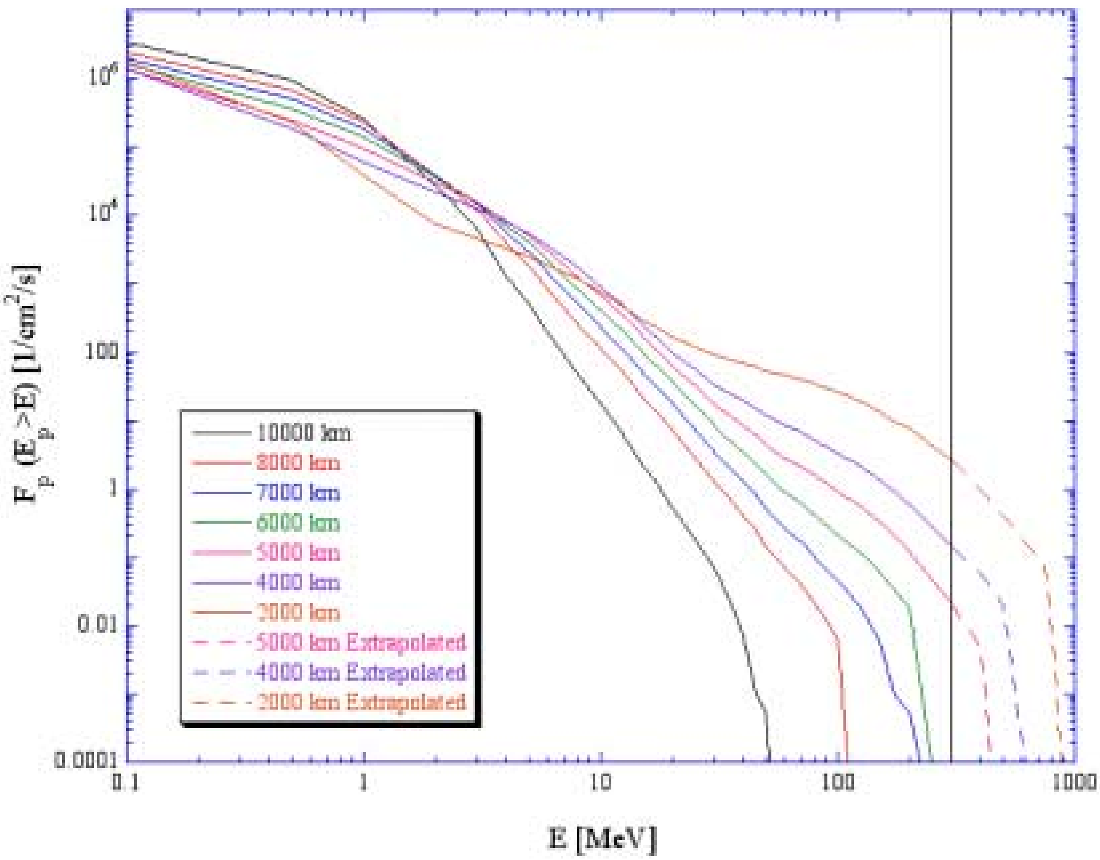


Figure 2: The integral proton flux spectra used to model radiation belt passages for contingency orbits. Details are given in the text.

that a radiation belt passage takes about 1 h (according to H. Evans, ESA ESTEC, the passage of the >10 MeV region of the radiation belt takes about 1.5% of the orbital period). In addition, isotropy was assumed for the radiation belt protons.

2.2 Contingency Orbits

Orbit-averaged proton spectra for radiation belt passages as a function of perigee height are given in Table 14 in *INTEGRAL Radiation Environment, Issue #4* by H. Evans, ESA ESTEC (see Fig. 2). This document also provides the durations of passages through the >10 MeV region of the proton belts at different altitudes, which is about 1 h. Unfortunately, the integrated proton spectra only cover energies up to 300 MeV. The most penetrating protons are those with the highest energies; these are also most important regarding activation of material close to the detectors or of the Ge crystals themselves. To better represent the highest energies an "extrapolation by eye" (indicated by the dashed lines in Fig. 2) was performed on proton spectra for perigees of 5000 km and below. As above, isotropy was assumed for the radiation belt protons.

3 Investigating the Effect of the Initial Perigee Height

3.1 Simulation Results

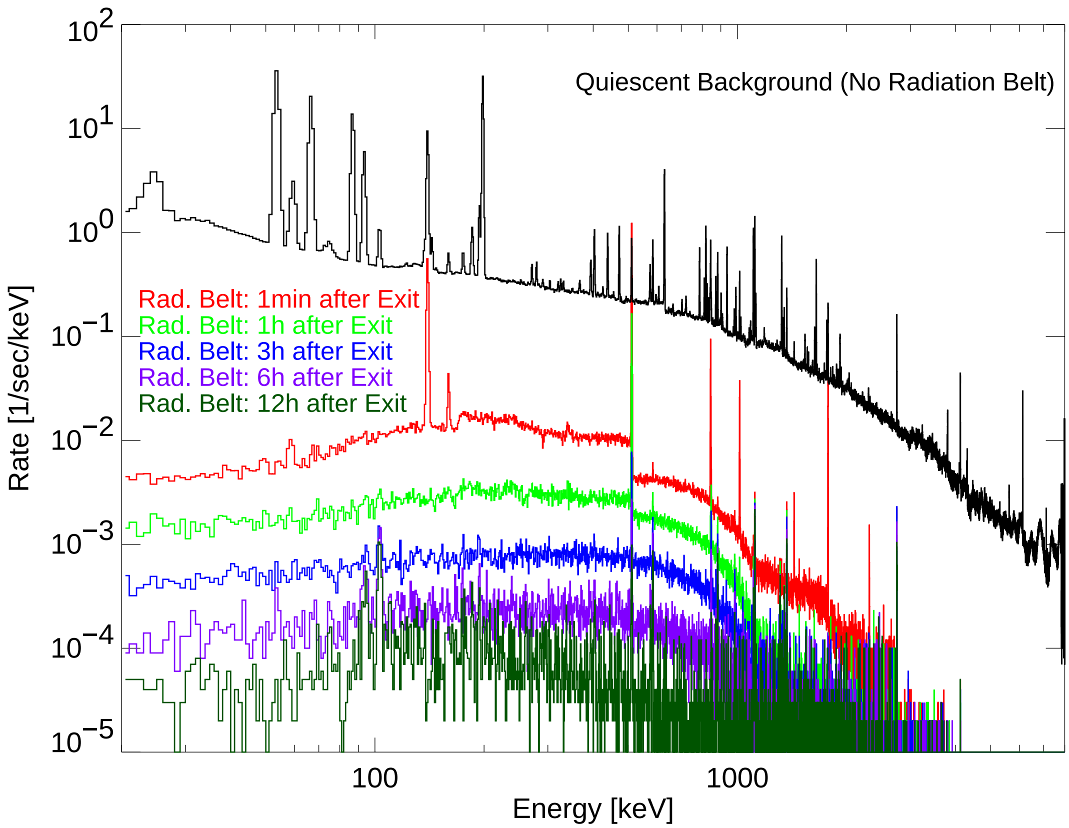


Figure 3: A comparion of the quiescent instrumental background to the background due to activation during radiation belt passages for an initial perigee height of 8500 km. The latter is shown at different times after exiting the radiation belt.

The instrumental background due to activation in all of the SPI instrument during radiation belt passages was studied for two initial perigee heights: 8500 km and 9500 km. The lowest, 8500 km, perigee results in the deepest radiation belt passage and hence the highest activation. This is the worst case scenario in which initial propellant consumption is assumed to be critical. The 9500 km perigee study provides an upper limit on the radiation belt background in case initial propellant consumption is not critical and both the 9500 km perigee and – even better for science – the 10,000 km perigee are feasible. For both perigees the radiation belt background was simulated at different times (1 min, 1 h, 3 h, 6 h, 12 h, and 1 d) after exiting the radiation belt, assuming the worst case proton spectrum described in Sec. 2.

A comparison of an estimate of the quiescent instrumental background (which does not include any effects from the radiation belt) to the simulated background due to activation in the radiation belt for an initial perigee heigth of 8500 km is shown in Fig. 3. Fig. 3 shows the salient features of the radiation belt background:

- The overall continuum background due to radiation belt passages is at an insignificant level compared to the quiescent background. The largest contribution occurs right after exit around several 100 keV and does not exceed a few percent.

- Radiation belt passages result in a few strong but short-lived instrumental lines and a few long-lived lines, both of which are discussed in more detail below. By nature the short-lived lines decay away rapidly. Two long-lived lines are of concern for science: the instrumenal 511 keV line for studies of Galactic positron annihilation, and the instrumental 846.8 keV line for supernova ^{56}Co spectroscopy.

The main instrumental lines – except the 511 keV line – are summarized in Table 1. Most of these lines are not expected to have any detrimental effect on γ-ray line spectroscopy because they do not coincide with the energies of lines of potential astrophysical interest. The main exceptions are the 159 keV background line from ^{77m}Ge, which coincides with a possible line signal from ^{56}Ni at 158 keV, and the 847 keV and 844 keV background lines from ^{56}Co and ^{27}Mg, which blend with a line signal from ^{56}Co at 847 keV. Because of its short half-life the ^{77m}Ge background line decays away quickly after exiting the radiation belt and can therefore be readily eliminated for investigations of ^{56}Ni production in supernovae.

The situation is more complex for spectroscopy of the 847 keV line from nucleosynthetic ^{56}Co. Similar to ^{77m}Ge, ^{27}Mg has a short half-life and its 844 keV background line is insignificant about 3 h after exit from the radiation belts, even for the lowest perigee height of 8500 km (see Fig. 4). In contrast, ^{56}Co has a half-life that is much longer than the orbital period. Although the ^{56}Co production during a single radiation belt passage does not result in a significant contribution to the quiescent background around 847 keV (compare Figs. 3 and 4), the repeated activation of ^{56}Co in consecutive radiation belt passages will result in a build-up. In the worst case, assuming an initial perigee height of 8500 km and no orbital evolution, the activity of radiation belt produced ^{56}Co would be a factor 1.5 higher than that of ^{56}Co produced by primary cosmic rays (see Fig. 5). However, because of orbital evolution, the long-term contribution of radiation belt produced ^{56}Co is expected to be smaller. In addition, the activation of ^{56}Co is very sensitive to the perigee height: for a perigee of 9500 km it is about a factor of 18 lower than for a 8500 km perigee. Spectroscopy of ^{56}Co from supernovae, which will produce a broadend 847 keV line, is also affected by the quiescent 844 keV background line from ^{27}Mg that is about 8 times stronger than the quiescent 847 keV background line.

Investigations of Galactic positron annihilation will also be impaired by radiation belt passages, which result in the activation of a number of isotopes that give rise to an instrumental 511 keV line (see Table 2). The decay of the instrumental 511 keV line due to activation during radiation belt passages is compared to the quiescent 511 keV line background in Fig. 6. Within the first few hours after exiting the radiation belt the quiescent 511 keV line background is significantly increased. At these early times after exit, the main contributors to the radiation belt 511 keV line background are ^{11}C and to a much lesser extent ^{13}N. Between 1 min and 1 h after exit the characteristic decay time of the 511 keV radiation belt background line is practically identical to that of ^{11}C, between 1 h and 3 h the characteristic decay time is about 26 min. For the lowest perigee it takes about 4 h for the radiation belt produced 511 keV line background to decrease to less than 1 percent of the quiescent background.

Decay	Half-Life	Line Energy [keV]
	Inside Ge Crystals	
^{75m}Ge(IT)^{75}Ge	47.7 s	140
^{77m}Ge(IT)^{77}Ge	52.9 s	159*
^{69}Ge(EC)^{69}Ga	39 h	584, 882, 1117, 1347 (note: γ-ray + X-ray)
	Outside Ge Crystals	
^{201}Bi(EC)^{201}Pb	59.1 min	279.1, 629.1, 786.4, 936.2, 1325.1, 1650.9
^{27}Mg(β^-)^{27}Al	9.5 min	844*, 1015
^{56}Co(EC)^{56}Fe	77.3 d	847*
^{27}Si(EC)^{27}Al	4.1 s	1015
^{52m}Mn(EC)^{52}Cr	21.2 min	1434
^{52}V(β^-)^{52}Cr	3.8 min	1434
^{28}Al(β^-)^{28}Si	2.2 min	1779
^{14}O(EC)^{14}N	70.6 s	2313
^{24}Na(β^-)^{24}Mg	14.9 h	1369, 2754

Table 1: The main instrumental lines (except the 511 keV line) produced during radiation belt passages.
* indicates background lines that may interfere with lines of astrophysical interest.

Decay	Half-Life	Production Site
^{69}Ge(EC)^{69}Ga	39 h	inside and outside Ge crystals
^{11}C(β^+)^{11}B	20.4 m	C in carbon fiber, honeycombs, "plastics", ...
^{13}N(β^+)^{13}C	9.97 m	C (as ^{11}C) and O in BGO
^{44}Sc(EC)^{44}Ca	3.97 h	Ti in Ti alloy used for mask support, brackets, screws, ...
^{45}Ti(EC)^{45}Sc	3.1 h	Ti and V in Ti alloy as above
^{47}V(EC)^{47}Ti	32.6 m	Ti and V in Ti alloy as above
^{48}V(EC)^{48}Ti	16 d	Ti and V in Ti alloy as above
^{64}Cu(EC)^{64}Ni	12.7 d	Cu in electronics, wiring, Al alloy, ...

Table 2: The main sources of the instrumental 511 keV line produced during radiation belt passages.

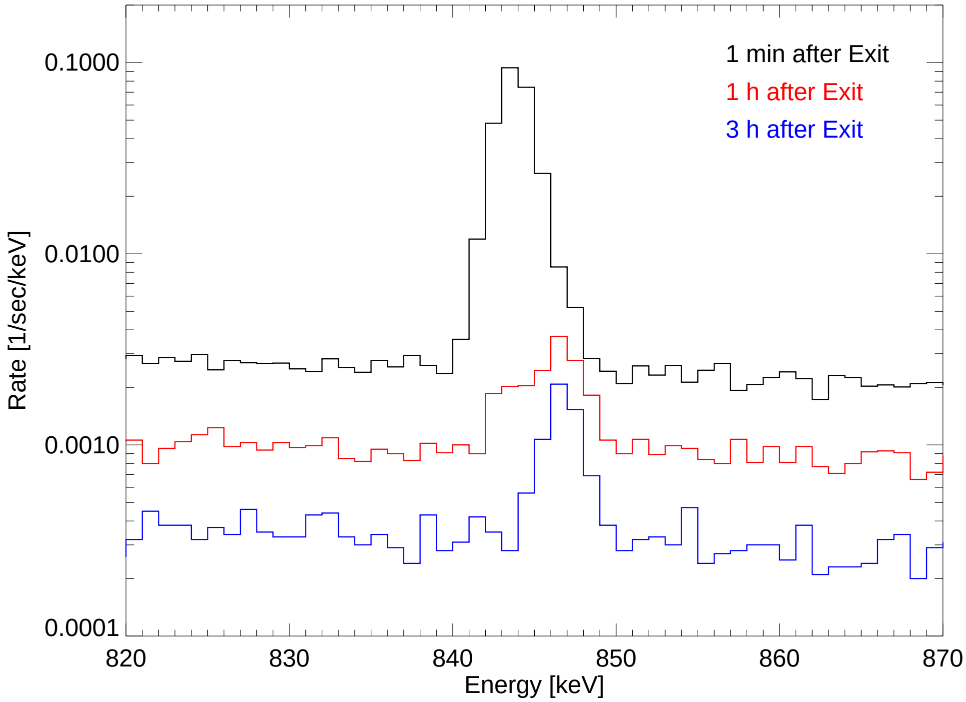


Figure 4: The time evolution of the radiation belt background around 846.8 keV, the rest energy of the strongest ^{56}Co line, after exiting the radiation belt for an initial perigee heigth of 8500 km. Details are given in the text.

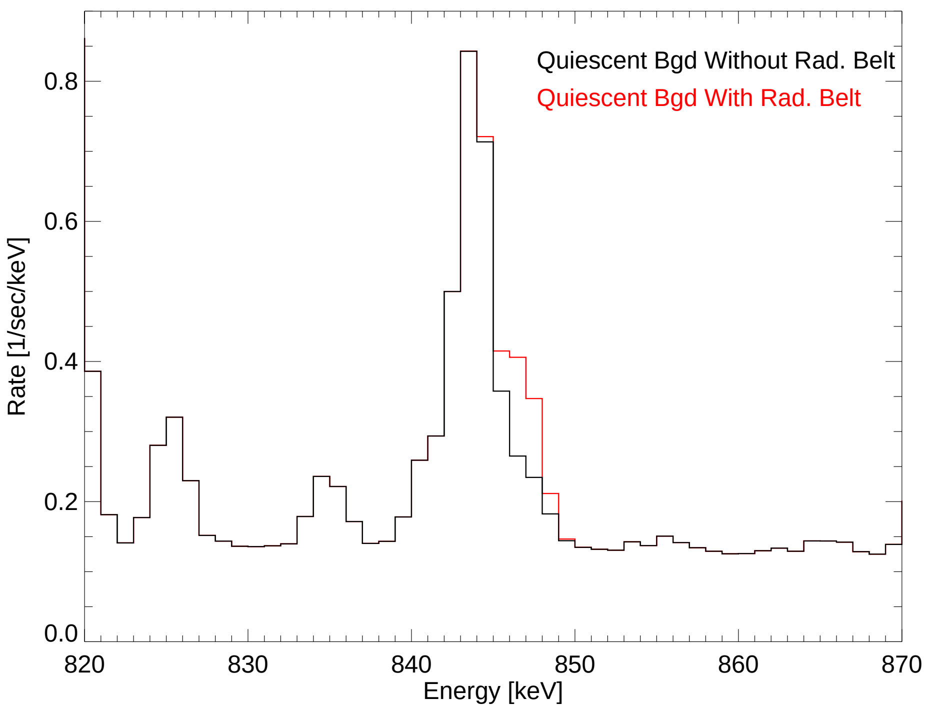


Figure 5: The quiescent background in the 846.8 keV region compared to the sum of the quiescent background and the ^{56}Co line background from radiation belt pasages after reaching radioactive equilibrium.

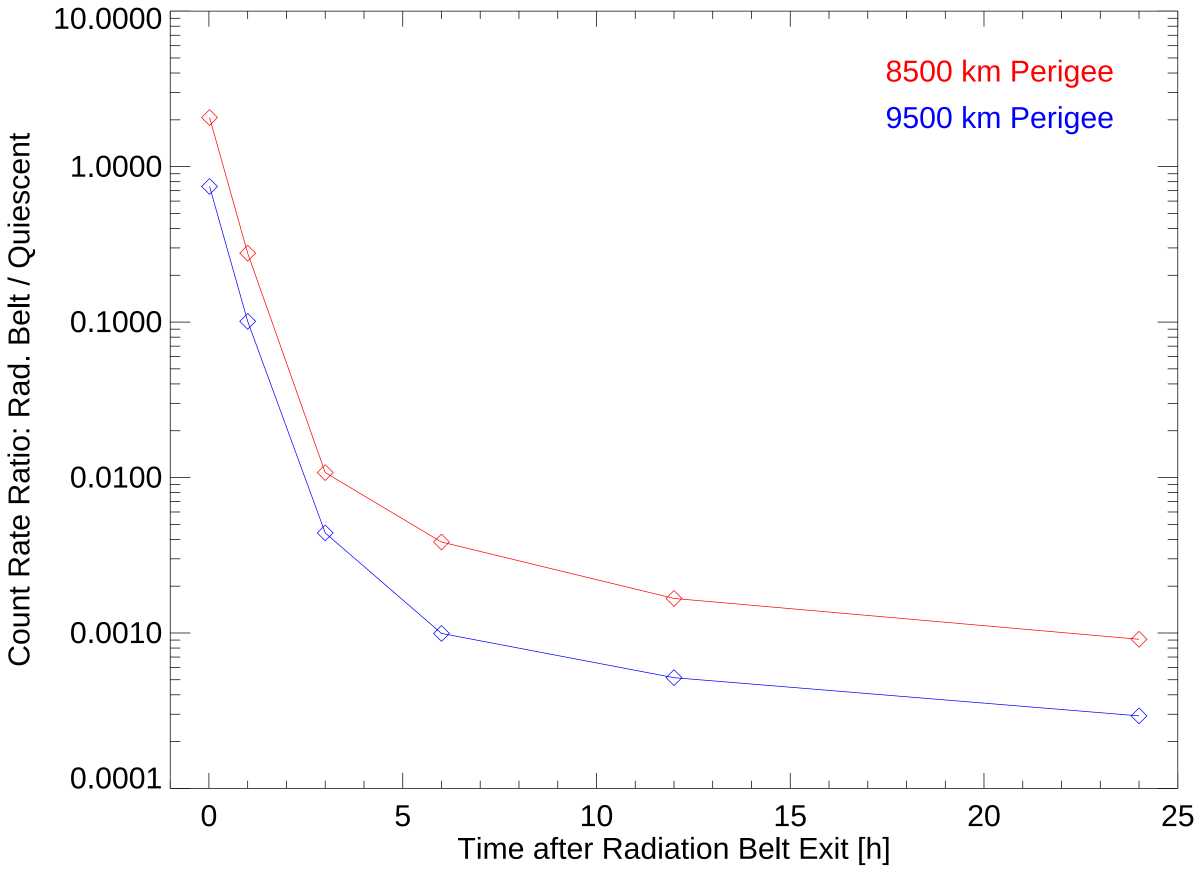


Figure 6: A comparion of the quiescent count rate in the 511 keV background line to the 511 keV line count rate due to activation during radiation belt passages for two perigee heights: 8500 km and 9500 km. Plotted is the ratio of the latter divided by the quiescent line rate as a function of time after radiation belt exit. The solid lines are supposed to guide the eye.

3.2 Summary

The effects of radiation belt passages on the SPI instrumental background can be summarized as follows:

- The quiescent continuum background is not significantly increased. Even the worst increase, which occurs right after exiting the radiation belt at energies of several 100 keV for an initial perigee height of 8500 km, does not exceed a few percent. For any of the initial perigee heights studied the radiation belt continuum background is less than 1% of the quiescent continuum background 1 h after exit.

- Radiation belt passages result in a number of strong intrumental lines. Two long-lived lines are of concern for γ-ray spectroscopy. For a low initial perigee the build-up of radiation belt produced ^{56}Co can result in a significant increase of the intrumental background at 847 keV and impair spectroscopy of nucleosynthetic ^{56}Co from supernovae. Activation during radiation belt passages results in a 511 keV background line which remains significant for a few hours (about 2–4 h depending on the perigee height) after exiting the radiation belt.

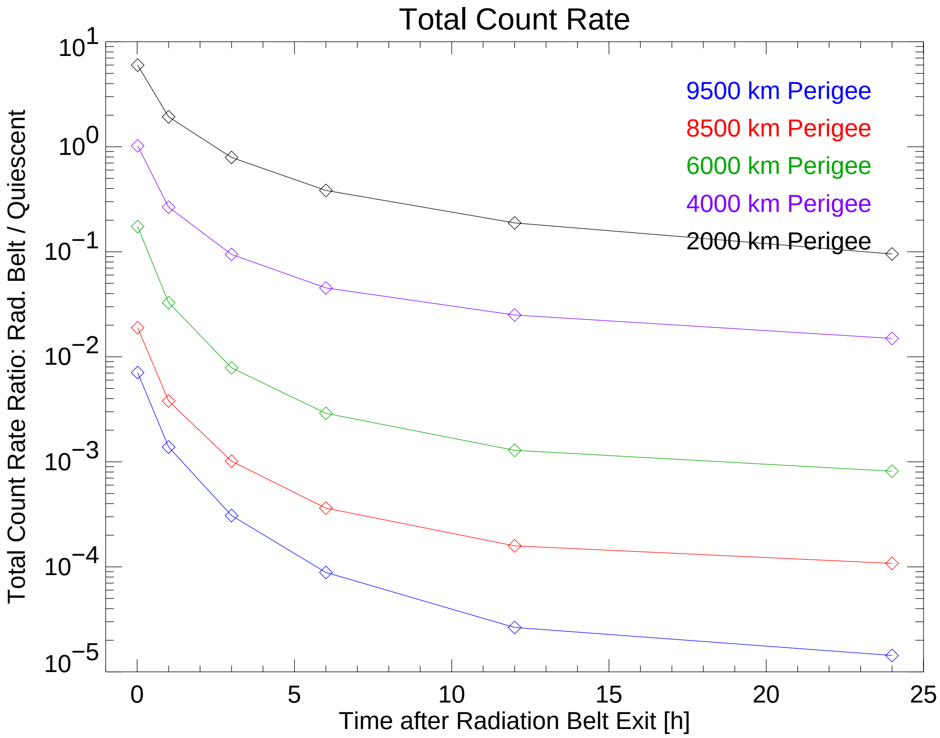
4 Contingency Orbits

The instrumental background due to activation in all of the SPI instrument during radiation belt passages was studied for three perigee heights: 2000 km, 4000 km, and 6000 km. The lowest perigee is also of interest for the low-Earth orbit phase following a successful launch, since a radiation belt passage with a perigee height of 2400 km is expected for October 25, following the first perigee raise burn on the previous day. Five days later the activation and tuning of the SPI anti-coincidence system will commence.

For the three perigee heights mentioned above the radiation belt background was simulated at different times (1 min, 1 h, 3 h, 6 h, 12 h, and 1 d) after exiting the radiation belt. In addition, because of its relevance for the low-Earth orbit phase operations, the background at 7 d, 14 d, and 21 d after exiting the radiation belt was estimated for a perigee height of 2000 km.

The time evolution of the total 20–8000 keV count rate in the radiation belt background, and of the 511 keV line rate, is shown in Fig. 7 for five different perigee heights (the curves for the 8500 km and 9500 km perigees are based on the studies described in Sec. 3.1, the 511 keV line results are those from Fig. 6). Both radiation belt background components increase with decreasing perigee height, as expected from the increase and hardening of the proton spectrum (see Fig. 2). In case of launch problems perigee heights below 4000 km would significantly impact observations with SPI. Even one day after exiting the radiation belt both backgrounds would still be a few percent of the quiesent background, and due to radioactive build-up this fraction would increase over time.

In case INTEGRAL is launched successfully, a radiation belt passage with a perigee height of 2400 km is expected for October 25. An upper limit to the longterm effect of the instrumental background induced by this passage is given in Fig. 8, which depicts the total count rate in the radiation belt background, and the 511 keV line rate, for a 2000 km perigee up to 21 days after radiation belt exit. Within a week the total count rate due to the 2400 km perigee height radiation belt passage can be expected to be less than 2% of the quiescent background rate. For the instrumental 511 keV line the situation is even slightly more favorable: the radiation belt background contribution should be less than 1% within one week. However, even after one week the radiation belt background can still contribute significantly to specific instrumental lines, as illustrated in Fig. 9.



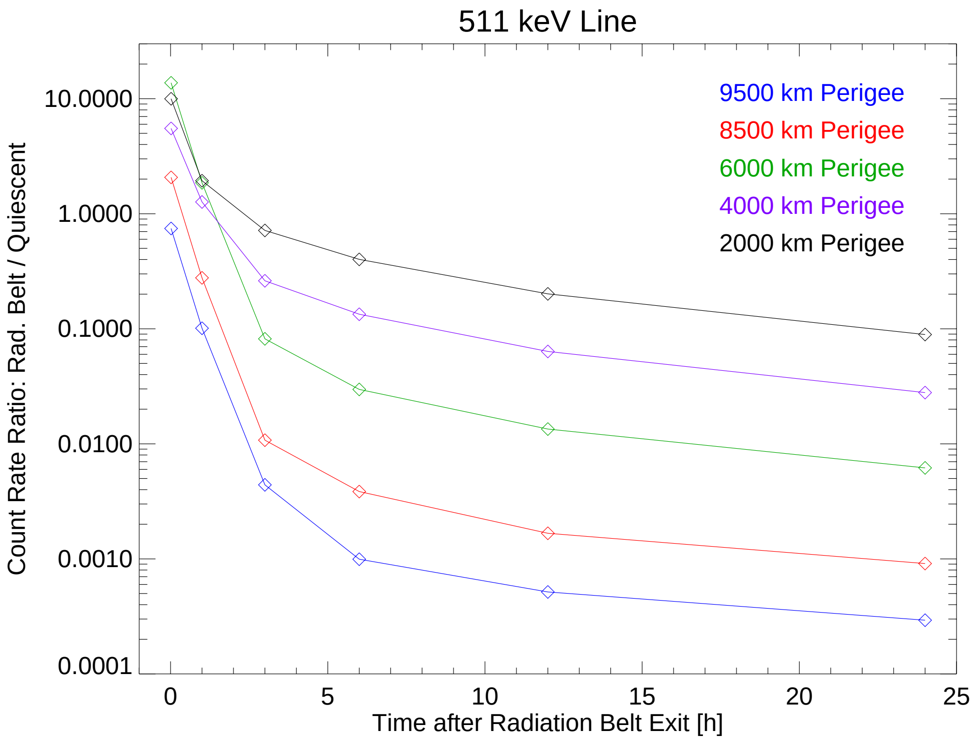


Figure 7: The time evolution of the total 20–8000 keV count rate in the radiation belt background (top) and of the 511 keV line rate (bottom) for five different perigee heights. Shown are the ratios of these quatities to the respective quiescent background components. The solid lines are supposed to guide the eye.

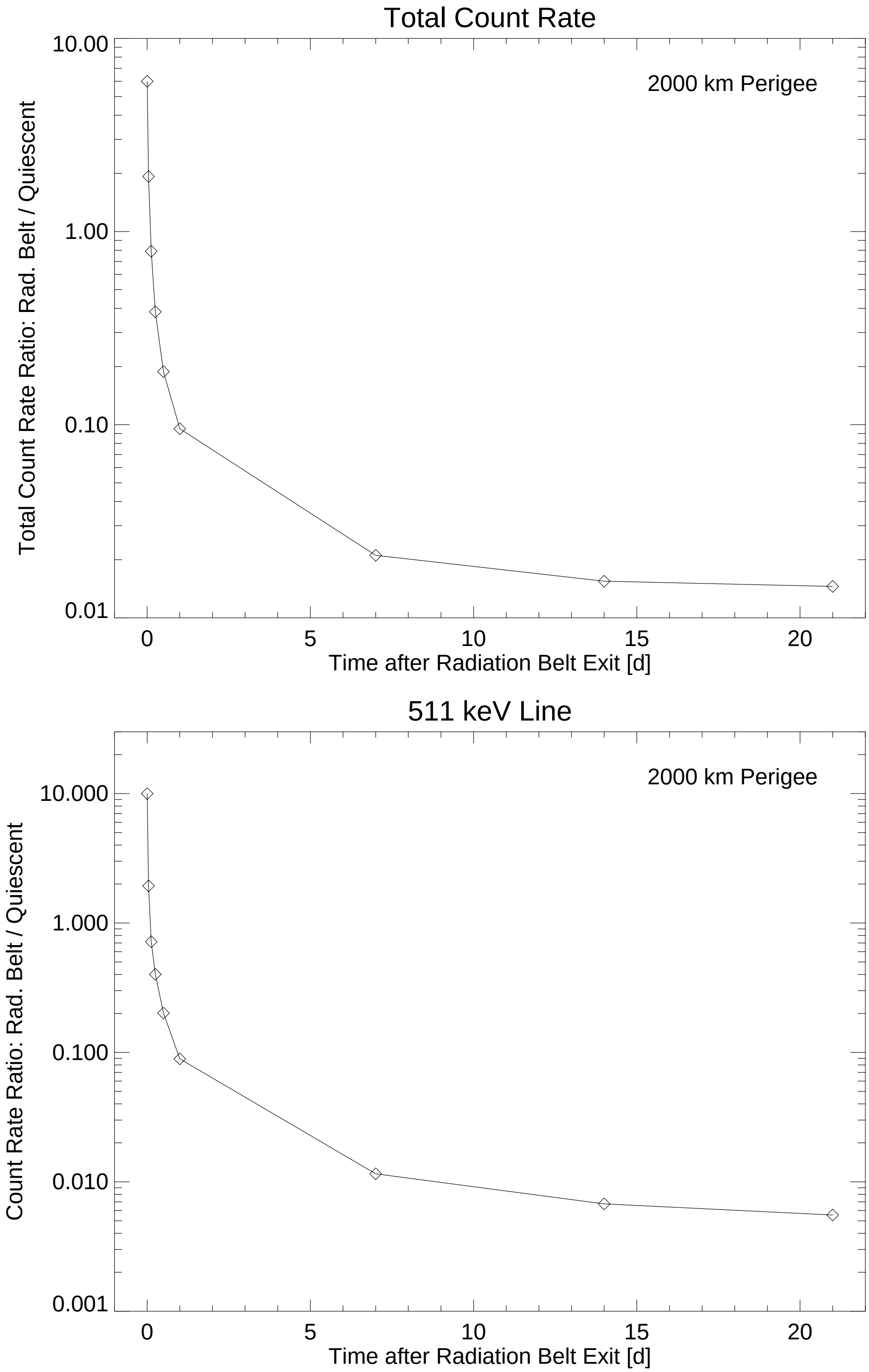


Figure 8: The longterm evolution of the total 20–8000 keV count rate in the radiation belt background (top) and of the 511 keV line rate (bottom) for a perigee height of 2000 km. Shown are the ratios of these quatities to the respective quiescent background components. The solid lines are supposed to guide the eye.

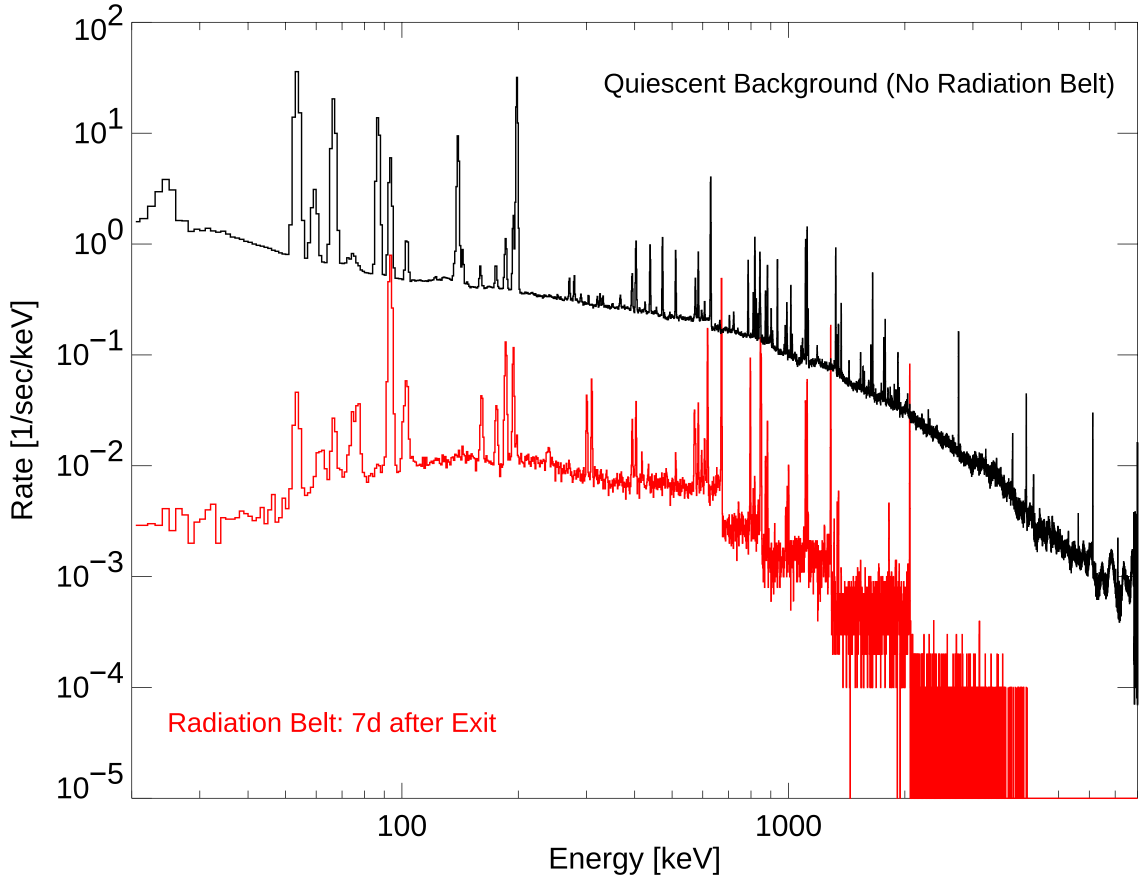


Figure 9: A comparison of the quiescent background with the radiation belt background 7 days after belt exit for a perigee height of 2000 km.