CAN THE INTEGRAL-SPECTROMETER SPI DETECT SUPERNOVA SIGNATURES IN THE COSMIC-DIFFUSE GAMMA-RAY BACKGROUND?

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ABSTRACT

Although recently a big step forward in the accurate measurement of the spectrum of the cosmic-diffuse low-energy (100 keV - 10 MeV) γ-ray background (CDB) has been made, its origin is still not yet well understood. Cosmological supernovae, among other source classes, are being discussed as possible contributors in this energy range. In these violent explosions radioactive nuclei are produced which decay emitting copious γ-rays. These γ-rays could provide a significant fraction of the CDB around 1 MeV. The calculated spectrum of the integrated emission shows characteristic steps or edges at clearly-defined energies. These features result from the integrated line emission at different redshifts. Here it is investigated if these structures can be detected with the INTEGRAL-spectrometer SPI. First results of this work will be presented.

Key words: INTEGRAL; SPI; cosmic-diffuse background; supernovae.

1. INTRODUCTION

After it has been predicted by Clayton, Colgate & Fishman (1969) that γ-rays may be generated in young supernova remnants, it was shown by Clayton & Silk (1969) that these γ-rays may provide a significant fraction of the CDB around 1 MeV. In their paper the contribution from cosmological supernovae was estimated by integrating over the redshift z. This idea was taken up again by Clayton & Ward (1975) and a first coarse energy spectrum of this contribution was calculated. The remarkable finding of this paper was that this spectrum showed significant structures (sharp steps and a characteristic dip) which - if measured - would allow an identification of this background contributor. A more refined calculation taking into account the emission spectrum of the γ-rays escaping a supernova remnant was performed by The, Leising & Clayton (1993). They confirmed the earlier findings and stated that the contribution of type Ia supernovae (SN Ia) to the background may be dominant around 1 MeV. They speculated already that a "very accurate measurement of the cosmic background spectrum between 0.1 and 1 MeV may reveal the turn-on time and the evolution of the rate of type Ia supernova nucleosynthesis in the universe". However in their paper they showed that the structures predicted by Clayton & Ward (1975) are less prominent than thought at that time. This trend was confirmed and even strengthened by the calculations of Watanabe et al. (1997, 1999). Especially the features at high redshifts (i. e. low energies) which depend also on the cosmological parameters are completely smeared out because of the spread of the turn-on times (i. e. the nucleosynthesis did not begin abruptly) of supernova explosions. But some, although weak, features remained at the high-energy side which correspond to the rest energies of the emitted lines due to the local SN activity (see Figure 3). Here it is investigated if these structures can be identified with the high-resolution spectrometer SPI of INTEGRAL.

2. SUPERNOVA FEATURES IN THE CDB

Several billion years ago supernovae began for the first time to explode in the universe. An interesting question is when this era began. The answer to this question may be found in a signature these supernovae may have imprinted in the CDB. In each of these huge explosions, especially during SN Ia explosions (thought to be the disruption of a white dwarf) radioactive elements are synthesized and expelled into the interstellar space. These elements decay emitting γ-rays with a typical energy E_γ. Depending on the emission epoch these γ-rays are redshifted: $E_{obs} = E_\gamma/(1+z)$.

In a typical SN type Ia explosion ~0.5 $M_\odot$ of ^{56}Ni is created. The radioactive ^{56}Ni decays to ^{56}Fe accord-

Table 1. The most important γ-ray lines produced during a supernova explosion.

line energy [MeV]	radioactive nucleus -	photons/decay -
0.15838	^{56}Ni	0.9881
0.84678	^{56}Co	0.9995
1.23828	^{56}Co	0.6757
2.59858	^{56}Co	0.1689
>3.61180	^{56}Ni, ^{56}Co	0.0

ing to ^{56}Ni $\rightarrow$ ^{56}Co $\rightarrow$ ^{56}Fe emitting among others strong and intense γ-ray lines (see Table 1). Beyond 3.6 MeV no γ-ray lines are produced anymore. Since supernovae are exploding more or less continuously one expects in the spectrum generated by these γ-rays - neglecting for the moment all other effects - a spectrum with two sharp edges:

- one at the rest energy E_γ (z = 0)
- one at the red-shifted energy $E_{obs} = \frac{E_\gamma}{(1+z_{onset})}$

The measurement of these edges would prove that cosmological supernovae contribute to the cosmic-diffuse γ-ray background radiation, would allow to quantify this contribution and in addition would allow the determination of z_{onset}. Since the redshift z is related to the cosmic time one can immediately calculate the age of the universe when the first supernovae started to explode. Unfortunately in reality these edges will be less pronounced because of the following effects:

- the onset time of supernovae is spread (The, Leising & Clayton, 1993)
- the emitted γ-ray lines are Compton-scattered in the supernova ejecta
- spatial and temporal fluctuations of the supernova explosions near z = 0 smear the corresponding edge.

3. COMPARISON OF THE CDB WITH THE SPI BACKGROUND

In Figure 1 three spectra are compared. The bottom spectrum is the spectrum of the superposed emission of cosmological SNe Ia according to the calculations of Watanabe et al. (1999). The two spectra in the middle are the cosmic-diffuse γ-ray spectra as measured by SMM (Watanabe et al. 1997) and COMPTEL (Weidenspointner 1999). The top spectrum is the background spectrum of the spectrometer SPI as simulated by P. Jean (private comunication) excluding the CDB. It is obvious that the SPI background dominates the cosmic-diffuse γ-ray background by a factor of ~30 above 1 MeV. This large signal-to-noise ratio makes the search for the SN signature a difficult task. This search is even aggravated by the complex structure of the internal background spectrum. This

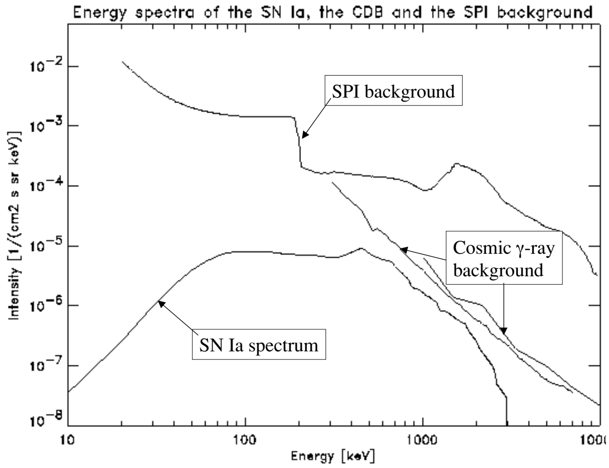

Figure 1. Intensity spectra of the SN Ia, the CDB and the SPI background.

is illustrated by showing a background spectrum of a TGRS Ge-detector (see Figure 2). The inserts show the complicated structures in the regions of interest around 847 keV and 1.238 MeV).

4. THE PROBLEM

In Figure 3 the spectrum of the SN contribution to the CDB according to Watanabe et al. (1999) is shown. The problem to measure the onset time of SN explosions or even to detect a possible contribution of these SNe to the CDB is obvious:

- No structures are visible at high redshifts (i. e. at low energies) $\Rightarrow$ onset time of SN not measurable!
- The edges at z = 0 are not sharp, but extend over an energy region of ~100 keV (much larger than the energy resolution of SPI).
- Only the lines at 847 keV, at 1.238 MeV and at 2.599 MeV produce edges which are sufficiently pronounced to be detectable.
- The SPI background is much higher than the CDB (see Figure 1).

The fact that the edges are not sharp may have something to do with the model calculation. The SN Ia spectrum used by Watanabe et al. (1999) for their calculation had a rather crude energy binning compared to the one of SPI. Moreover large uncertainties are contained in many of the assumptions that went into this calculation. All this may smear possible sharp edges. But also some physical effects like the star-formation history and the delay time between the star formation and the SN explosions may conceal these sharp edges. However, similar calculations performed recently by Ruiz-Lapuente et al. (2000) led also to such sharp edges.

Another severe problem is the last point because it will be very difficult to distinguish between the internal and the external background. The external (i. e. diffuse) background is as isotropic as the in-

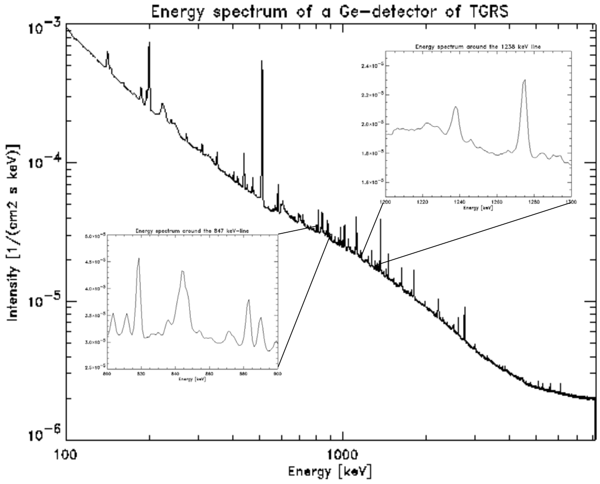

Figure 2. A background spectrum of the TGRS Ge-detector.

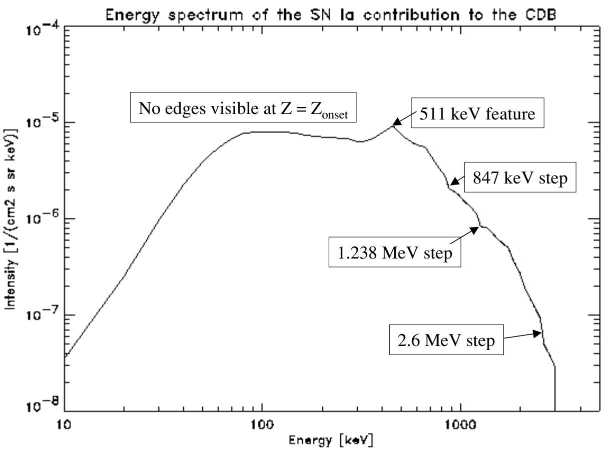

Figure 3. The intensity spectrum of the SN Ia contribution to the CDB.

ternal background and SPI's mask cannot throw a characteristic shadow on the detector. Therefore no independent method exists to determine and to reduce the internal background. Aggravating is the fact that the internal background will very probably have structures of its own (see Figure 2). So even if one finds structures in the measured spectrum its origin may remain unknown. The only clue to this problem may come from simulations, but whether they are reliable enough is an open point.

In what follows these problems are discarded and a featureless and smooth internal background spectrum is assumed. Based on this assumption it is tried to estimate how long SPI has to measure the CDB in order to be able to detect an edge in the SN background contribution.

5. CALCULATION OF THE EFFECTIVE OBSERVATION TIME

For the following estimation it is assumed that the following parameters are known:

- The energy E_{step} at which an intensity step occurs.
- The height $\Delta I(E_{step})$ of the intensity step.
- The cosmic-diffuse background spectrum I_{diff}.
- The internal background spectrum F_{SPI}.
- SPI's energy resolution ΔE as a function of energy.

The task is now to estimate the effective observation time T_{eff}.

The number of counts in an energy interval ΔE_l and ΔE_h below and above a step energy E_{step} can be calculated as follows:

$$N_l = (I^l_{diff} \cdot \Delta\Omega + F^l_{SPI}) \cdot A_{eff} \cdot T_{eff} \cdot \Delta E_l \quad (1)$$

$$N_h = (I^h_{diff} \cdot \Delta\Omega + F^h_{SPI}) \cdot A_{eff} \cdot T_{eff} \cdot \Delta E_h \quad (2)$$

A_{eff} is the effective area, T_{eff} the effective observation time and $\Delta\Omega$ the field of view of SPI. The error of the difference $\Delta N = N_l - N_h$ is given by

$$\Delta(\Delta N) = \sqrt{\Delta N_l^2 + \Delta N_h^2} = \sqrt{N_l + N_h} \quad (3)$$

The intensity of the background radiation is given by the sum of the cosmic background intensity I_{cosm} assumed to be constant in the energy range of interest and the intensity I_{SN} from the supernovae.

$$I^l_{diff} = I_{cosm} + I^l_{SN} \quad (4)$$

$$I^h_{diff} = I_{cosm} + I^h_{SN} \quad (5)$$

The difference of the two intensities is then:

$$\Delta I = I^l_{diff} - I^h_{diff} = I^l_{SN} - I^h_{SN} \quad (6)$$

In order to detect a jump or edge in the measured spectrum with sufficient statistics (3σ) the following relation must at least hold:

$$3 \cdot \Delta(\Delta N) < \Delta I \cdot A_{eff} \cdot T_{eff} \cdot \Delta\Omega \cdot \Delta E \quad (7)$$

Inserting equations (3) and (6) into (7) and solve it for the effective observation time T_{eff} one obtains:

$$T_{eff} > \frac{9 \cdot [(I^l_{diff} + I^h_{diff}) \cdot \Delta\Omega + F^l_{SPI} + F^h_{SPI}]}{\Delta I^2 \cdot \Delta\Omega^2 \cdot A_{eff} \cdot \Delta E} \quad (8)$$

6. RESULTS

Since the intensity steps in Figure 3 are not sharp, but extend over a certain energy range, they had

Table 2. The calculated (extrapolated) intensity steps at three step energies [= $\gamma/(cm^2\ s\ sr\ keV)$].*

E_1 [keV]	E_2 [keV]	E_{step} [keV]	extrapolated $I(E_{step})$ [*]	Δ I [*]
780	820	847	$2.67 \cdot 10^{-6}$	$5.2 \cdot 10^{-7}$
880	920	847	$2.15 \cdot 10^{-6}$	
1160	1200	1238	$1.07 \cdot 10^{-6}$	$2.26 \cdot 10^{-7}$
1260	1300	1238	$8.41 \cdot 10^{-7}$	
2420	2460	2599	$8.04 \cdot 10^{-8}$	$2.9 \cdot 10^{-8}$
2640	2680	2599	$5.15 \cdot 10^{-8}$	

Table 3. The parameters used for the calculation of the effective observation time to obtain a 3σ signal.

E_{step} [keV]	ΔE [keV]	A_{eff} [cm^2]	F_{SPI} [$\gamma/(cm^2$ s keV)]	T_{eff} [years]
847	1.966	206	$3.1 \cdot 10^{-5}$	2.1
1238	2.15	176	$3.3 \cdot 10^{-5}$	12.6
2599	2.68	117	$2.2 \cdot 10^{-5}$	613

to be calculated via extrapolations from two energy intervals (with limits E_1 and E_2) below and above E_{step}. For the extrapolation a simple power law was used. The result is given in Table 2.

In Table 3 the effective observation time for the observation of an intensity step with 3σ has been calculated using equation (8) with $\Delta\Omega = 0.28$ sr. This purely statistical estimation shows that one has to gather data for about two years to detect a step at 847 keV with 3σ. If one takes into account systematic effects and the complicated structure of the SPI background the chances for detecting each of these steps individually gets very small within the life time of SPI.

The statistical significance can be enhanced by exploiting the fact that three lines at known energies are expected. By combining their individual probabilities one can increase the overall detection probability. The statistical significance (i. e. the number of σ above background) for each line can be calculated from equation (7).

$$n = \frac{\Delta I \cdot A_{eff} \cdot T_{eff} \cdot \Delta\Omega \cdot \Delta E}{\Delta(\Delta N)} \qquad (9)$$

Calculating using (9) the probability $p_i(n\sigma)$ (i=1, 2, 3) that a certain σ-value is obtained for the three lines in Table 3 and combining the single probabilities according to (10) one finds the overall probability for detecting the edges in the SN spectrum as a function of T_{eff}.

$$p_{tot} = 1 - (1 - p_1) \cdot (1 - p_2) \cdot (1 - p_3) \qquad (10)$$

This probability respective the corresponding numbers of σ are shown in Figure 4. Another possibility

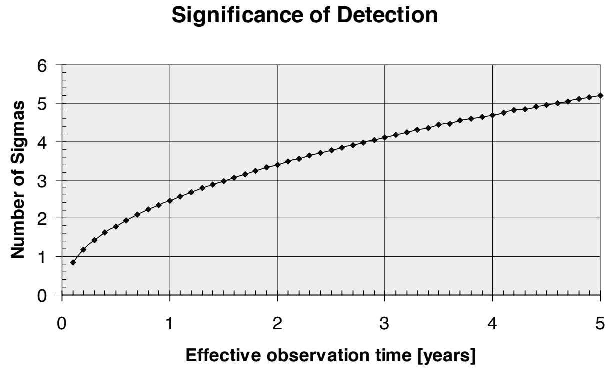

Figure 4. The overall detection significance as a function of time.

to increase the significance would be an increase of Δ E. This will be investigated in the future.

7. CONCLUSIONS

The effective observation time for the detection of a 3σ signal is about 1.5 years. This is well within the planned lifetime of SPI. So in principle the detection of the structures imposed on the CDB by cosmological SNe seems to be possible under the aforementioned assumptions for the combined effect.

8. ACKNOWLEDGMENTS

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