^{44}TI LINES IN THE *INTEGRAL* CORE PROGRAMME DATA

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ABSTRACT

The *INTEGRAL* core programme features a scan of the Galactic disc and deep exposures on the central Galactic radian and on the Vela region, including RX J0852.0-4622/GRO J0852-4642 (hereafter Vela junior). These accumulated data can be used to estimate some of the characteristics of the Cas A and Vela Junior SNRs through the measurement of their ^{44}Ti lines (68, 78 and 1157 keV). Furthermore the search for these lines in the surveys should reveal previously unknown young SNRs hidden at other wavelengths by the Galactic disc absorption or emission. The data on each SNR will give access to, or constrain, the expansion velocity, the age, the distance and the ^{44}Ti yield. A refinement of the SNR rate in the Galaxy should also result. This paper presents simulations performed to estimate the potential of the *INTEGRAL* payload and of the core programme to fulfil these goals.

1. INTRODUCTION

Full sky mapping in the continuum or line emission using the entire *INTEGRAL* database provides a global picture of the steady discrete sources and is important for identifying potential new candidate SNRs, which were not detected by optical or radio surveys. Nearly 400 years passed since a supernova was last directly observed in the Milky Way by Kepler in 1604. The mean Galactic supernova (SN) rate estimated by different authors ranges between 1 and 6 per century as derived by three different methods (van den Bergh 1988; van den Bergh and Tammann 1991; Müller et al., 1992; van den Berg 1996). For a mean Galactic rate of 2.5 SNe per century, assuming the Poisson distribution, the probability that not a single SN occurred in the Galaxy during the last 300 years is less than 6×10^{-4}. It is therefore plausible to assume that most of the Galactic SNe had occurred in highly obscured regions of the Galaxy and remained undetected.

Those SNe that probably flared before the 20-th century might have been observed only by optical telescopes or visually. Since the variable star Mira apparently was never observed in antiquity, it has been argued (Clark and Stephenson 1977) that an object had to reach at least $m_V = 1.5$ to be detected by ancient astronomers. The historical record of SNe is mainly drawn from Oriental sources and extends back to at least 200 BC (Clark and Stephenson 1977; Stephenson 1976; Strom 1994), but considered not to be complete (Stephenson 1976; Strom 1994). The case of Cas A could be examplified as the missed SN event, which may still have been seen by John Flamsteed at about 1680 AD (Ashworth 1980).

D. Helfand et al. (1989) discussed the prevalence of SNRs among unidentified Galactic radio sources and has drawn the conclusion that about 200 Galactic SNR are still to be identified. It is still true today even if a small percentage of SNRs already have been identified with *ROSAT* (Aschenbach 1996), or by the most recent radio survey (Duncan et al. 1995; Green 1998).

Young Galactic SNRs are difficult to identify by standard methods due to their apparently small angular extent (Sramek et al. 1992; Strom 1994). The radio emission can be detected from SNe only within a few years of maximum brightness and from SNRs with ages in excess of 300 years (Weiler et al. 1986; Weiler and Sramek 1988). Additionally, most radio surveys are limited to the narrow band along the Galactic plane.

In X-rays, ROSAT has demonstrated an excellent capability to reveal SNRs in nearby or unobscured regions of the Galaxy, but all X-ray SNRs found until now are rather old $\geq 10^3$ y (Aschenbach 1996). A number of young SNRs may have their X-ray emission below ~ 1 keV absorbed in surrounding and/or foreground interstellar matter. Therefore, other methods have to be introduced to search for young Galactic SNRs.

2. THE CONTRIBUTION OF GAMMA-RAY ASTRONOMY

In this respect the γ-ray line spectroscopy looks promising as it is exploiting much more penetrating photons to probe the potential nucleosynthesis sites. Young Galactic SNRs, possibly hidden due to the strong extinction in the Galactic plane, are among the most interesting candidate sources which eventually could be seen because of their ^{44}Ti γ-ray lines emission. The 1.16 MeV γ-ray line from the decay-chain of ^{44}Ti because of its ~90 years life-time (Ahmad et al. 1998; Görres et al. 1998; Norman et al. 1998; Whitfeldt et al. 1999), is probably the best indicator of young Galactic SNRs. The recent discovery of 1.157 MeV ^{44}Ti line emission from Cas A by COMPTEL (Iyudin et al. 1994) supports this view. ^{44}Ti is expected to be produced in different types of SNe, although with very different abundances depending on the mass-cut, up to 10^{-4} $M_{\odot}$ for the most frequent SNe of type

II and Ib (Woosley and Weaver 1995; Thielemann et al. 1996) and 8.9×10^{-3} $M_{\odot}$ for the rare event of the helium white-dwarf detonation (Woosley, Taam and Weaver 1986). It is interesting to note that not all ^{44}Ti-rich events may have optically bright light curves.

Because the ~ 90 y decay time of ^{44}Ti is comparable to the average time interval between Galactic SNe, ^{44}Ti γ-ray line emission should appear as localised sources rather than diffuse emission. The previous search for Galactic sources of ^{44}Ti γ-ray line emission along Galactic plane based on a three year accumulation of the COMPTEL data was not successful in finding new excesses apart from the already known detection of Cas A but has given a hint to the possible excess in the Perseus OB2 association (Dupraz et al. 1997). A more recent Galactic survey in the light of the ^{44}Ti-line emission has been undertaken with COMPTEL covering the interval from April 1991 to October 1997. In addition to Cas A, one significant excess of ^{44}Ti line emission was found in the Galactic survey (Iyudin et al. 1998), while one could expect to find 5 or more SNRs in addition to the historical record. We expect that ~ 6 out of 7 SNRs are produced in type II or Ib SN explosion, e.g. via explosion of rather massive progenitor stars ($M \geq 20\ M_{\odot}$). Such massive stars are usually present in OB associations with ages ≤ 3×10^{7} years. It is obvious from the sensitivity considerations that with COMPTEL we were sampling subset of the Galactic SNRs whose flux in the 1.157 MeV line emission, $F_{1.157\,\mathrm{MeV}} \geq 2\times10^{-5}$ cm^{-2} s^{-1}. By setting a limit to the distances of the prospective SNRs being ≤ 1 kpc, we are sampling SNRs with the age between ≤ 300 y for sources at ~ 1 kpc, and e.g. ≤ 700 y for sources in the nearest OB associations (Lower Centaurus Crux or α Persei).

Investigations of the Galactic SN rate will also benefit from such a survey. For example, the rate of SNe with ^{44}Ti emission can be compared with the SN rate from optical (historic) and radio observations. Recent study (The et al., 1999) has shown that the ^{44}Ti SN rate appears significantly lower than the otherwise-constrained general SN rate in the Galaxy. Thanks to the sensitivities of the *INTEGRAL* instruments, we expect that we can extend this study, especially in the inner Galaxy where a large part of the core programme, the Galactic Center Deep Exposure (GCDE) will be devoted.

A simple simulation has been built to estimate what can be expected from these *INTEGRAL* observations in the Cas A and Vela Junior directions. The two main instruments of *INTEGRAL*, IBIS and SPI, can both provide images and spectra over the same spectral range but each of them is specialised. IBIS is designed to provide a fine imaging (12′) with moderate spectroscopic performance while SPI offers high spectroscopy (E/ΔE = 500) with limited imaging capabilities. The sensitivity of the *INTEGRAL* telescopes to detect a line depends on the line shape and width as soon as the latter exceeds the detector resolution. The shape and width of the ^{44}Ti lines are governed by the Doppler shift and by absorption in the expanding ejecta of the ^{44}Ti. Since our purpose is only to evaluate the *INTEGRAL* possibilities, it is not necessary to use an accurate model for the expansion of the ^{44}Ti in the SNR. An infinitely thin shell expanding at the velocity V_{exp} offers the advantage of simplicity since in that case the line shape is a top hat function centred on E_0, the line energy at rest, with a width of $2\ E_0\ V_{exp}$ / c. The SPI and IBIS sensitivities have been taken from the ESA *INTEGRAL* Web site[1]

3. CAS A

Every week, *INTEGRAL* will survey the accessible part of the Galactic disc to look for bright transient events such as X-ray novae. Week after week, these Galactic Plane Scan (GPS) measurements will be piled up to produce a Galactic map with uniform exposure. After one year the observing time in any direction in the Galactic plane (except the central region) will attain 8.3×10^{4} s. Compared to the typical observing time of COMPTEL, this figure may seem limited but one should remember first that there are two instruments on-board *INTEGRAL*, each of them more sensitive than COMPTEL, and second that there are two more

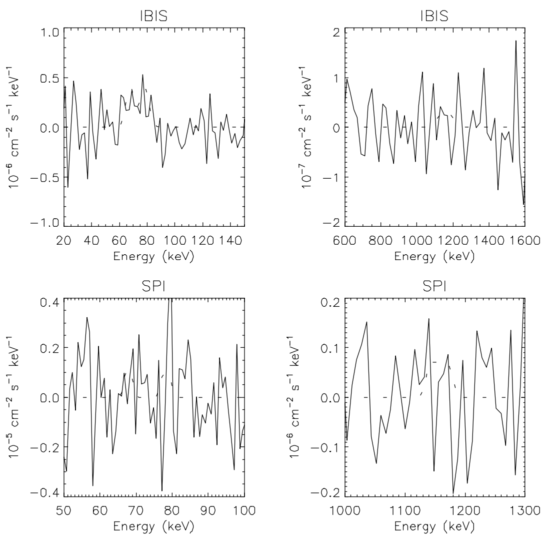

Figure 1:Model (dashed line) and simulated (continuous line) spectra of Cas A for 8.3×10^{4} s and V_{exp}= 6000 km s^{-1}.

[1]http://astro.estec.esa.nl/SA-general/Projects/*INTEGRAL*/*INTEGRAL*.html

^{44}Ti lines accessible to these instruments. Although the detection of the 1.157 MeV ^{44}Ti line from Cas A is firmly established by the COMPTEL observations, the line flux and the expansion velocity are uncertain and it is worthwhile to estimate what can be expected from the *INTEGRAL* core programme observations in direction of this SNR.
The line flux has been fixed to 3.3×10^{-5} cm^{-2} s^{-1} (Iyudin et al. 1997) and the expansion velocity was set successively to 3000, 6000 and 9000 km s^{-1}. The case $V_{exp} = 6000$ km s^{-1} is illustrated in Figure 1. The expected signal to noise ratio optimised using the 3 lines varies with V_{exp} from 2.5 to 1.7 for SPI while it is constant at 5.3 for IBIS.

4. VELA JUNIOR

Within the core program, a specific case has been made for the Vela region for its exceptionally rich content in interesting and nearby sources. Among them, one notes the presence of the rotation powered Vela pulsar, the accretion powered Vela X−1, γ Vel, the nearest WR star, the presence of an ^{26}Al emission maximum… and the Vela Junior SNR. The spatial distribution of this SNR in the ^{44}Ti lines is not known and various speculations can be made to illustrate the IBIS and SPI capabilities and complementarity.
It could be a point source for both IBIS and SPI if its extent is smaller than 12′ and if its flux is comparable to that of Cas A (Iyudin et al., 1998), its detectability would be then identical. Since 10^6 s from the core programme will be devoted to observe it during the first year of the *INTEGRAL* mission, the signal to noise ratio one can expect can be obtained by multiplying the values of table 1 by $(10^6 / 8.3\times10^4)^{1/2}$. That is 18.4 in the IBIS case and from 8.8 ($V_{exp} = 3000$ km s^{-1}) down to 5.9 ($V_{exp} = 9000$ km s^{-1}) in the SPI case. Figure 2 illustrates the corresponding simulated spectra.

If the source is more extended than the IBIS PSF, the visibility is lowered for IBIS but not for SPI as long as the extent is smaller than the SPI PSF. For example, if the distribution of the ^{44}Ti is a 2° diameter thin ring, at least 5×10^6 s would be necessary to reveal the shell as such in the IBIS image (see Figure 3). However, the shell might be inhomogeneous and the hot spots would be more easily detectable.

It is also possible that the explosion was axisymmetric (Nagataki et al., 1997) that would ease the detectability of the ^{44}Ti emission. In that case, if the expansion axis is close to the line of sight, IBIS would detect easily a point source in the image and SPI would detect two narrow lines around 1.15 MeV. The line separation would then provide the expansion velocity or a lower limit if the axis is not coincident with the line of sight. On the other hand if the expansion axis is orthogonal to the line of sight, two point sources may be visible in the IBIS image if they are separated enough while SPI would easily detect one narrow line in the spectrum. The SPI and IBIS complementarity, obvious here should help disentangling this SN

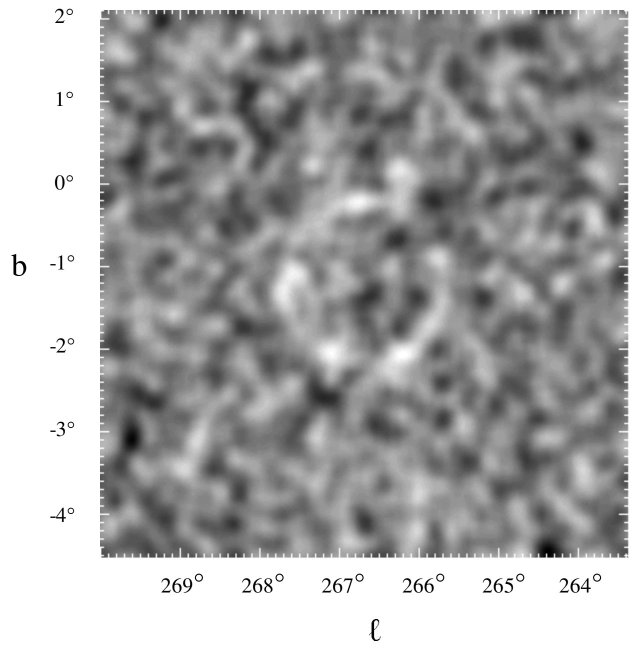

Figure 3: Simulated IBIS image of Vela Junior after 5×10^6 s. The shell is a ring of 2 deg. diameter.

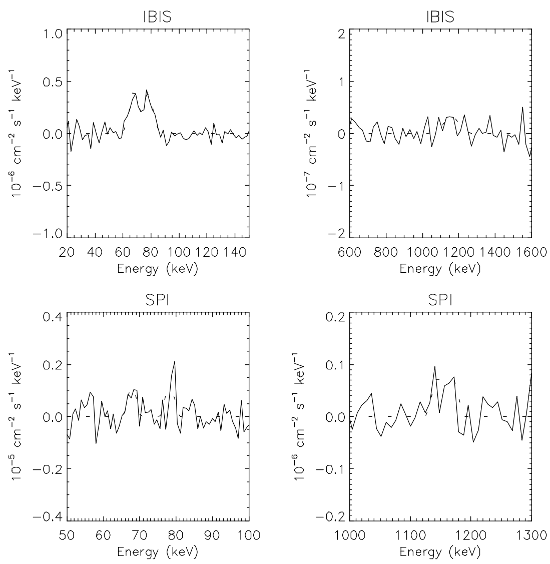

Figure 2 : Model (dashed line) and simulated (continuous line) spectra of Vela Junior for 10^6 s (after 1 year of INTEGRAL operations). The source extent is assumed to be smaller than the IBIS PSF width (12') and the expansion velocity is taken as 6000 km s^{-1}.

characteristics, namely the age, the ^{44}Ti yield, the expansion velocity and the distance. Moreover the Vela Junior case may provide a unique opportunity to check the consistency of the INTEGRAL payload calibrations and the analysis software since each instrument should detect 3 lines of approximately the same strength independently of the line widths and of the source extent.

5. HIDDEN YOUNG SUPERNOVAE

INTEGRAL will not only be able to measure the ^{44}Ti lines in the directions of Cas A and Vela Junior but its sensitivity should also permit the detection of fainter young SNe, hidden at other wavelengths. From the above simulations, it is clear that for reasonable expansion velocities (V_{exp} > 3000 km/s) the *INTEGRAL* sensitivity to the ^{44}Ti lines is provided by IBIS. Furthermore, this sensitivity is almost independent from the expansion velocity of the shell. Therefore, one can infer from our simulations that the 5σ IBIS sensitivity to the ^{44}Ti lines (essentially the low energy lines) is about 9×10^{-6} cm^{-2} s^{-1} for 10^6 s of observation (one year of the GCDE). Figure 4 illustrates the detectability of the ^{44}Ti lines as a function of the age and distance of a SN having produced 10^{-4} $M_{\odot}$ of ^{44}Ti. From this figure, it appears that any SN that exploded in the central radian during the 20th century should be detectable. Altogether, with the Galactic Plane Scan, *INTEGRAL* should detect several unknown SNe if their average ^{44}Ti yield is of the order of 10^{-4} $M_{\odot}$ and a few SNRs should still be detectable even for a two times smaller yield.

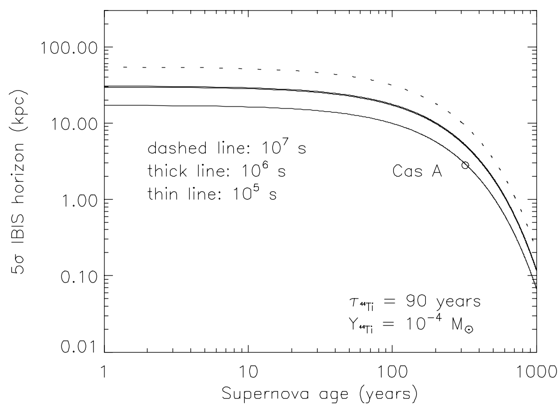

Figure 4: Distance at which a supernova of a given age could be detected by IBIS for various observing times. The observing time per year for any direction within the central radian of the Galaxy is 10^6 s and 8.3×10^4 s elsewhere.

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