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^{44}Ti nucleosynthesis gamma-ray lines with *SIMBOL-X*

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Abstract. In this contribution we discuss the ^{44}Ti nucleosynthesis γ-ray lines and their visibility with *SIMBOL-X* from simulations based on its expected sensitivity and spectro-imaging capabilities. The ^{44}Ti radioactive nucleus can provide invaluable information on the details of supernova explosions. Its lifetime of ~ 85 yrs makes it the best indicator of the youth of these stellar explosions through its three γ-ray lines at 67.9, 78.4 keV and 1.157 MeV. We focus on the youngest Galactic supernova remnants, namely: Cassiopeia A, for which the location and Doppler-velocity estimates of the ^{44}Ti-emitting regions in the remnant would offer for the first time a unique view of nucleosynthesis processes which occurred in the innermost layers of the supernova; SN 1987A, in the Large Magellanic Cloud, whose progenitor is known, and for which the expected measurement of these lines would greatly constrain the stellar evolution models; Tycho and Kepler SNRs for which ^{44}Ti lines have never been detected so far. The issue of the "young, missing and hidden" supernova remnants in the Galaxy will also be addressed using *SIMBOL-X* observations at the position of the ^{44}Ti excesses that wide-field instruments like those onboard *INTEGRAL* and *SWIFT*/BAT should be able to reveal.

Key words. gamma rays: observations – ISM: individual (Cassiopeia A, Tycho, Kepler, SN 1987A) – nuclear reactions, nucleosynthesis, abundances – supernova remnants

1. Introduction

Gamma-ray lines (from several tens of keV to MeV energies) emerging from radioactive nuclei are the unique way to provide isotopic information from sources and sites of cosmic nucleosynthesis and to probe several underlying key physical processes (see *e.g.* Diehl et al., 2006, for a recent review). Moreover, their highly penetrating nature allows astronomers to probe regions invisible at other wavelengths. The main candidate sources are novae, supernovae (hereafter, SNe), winds from massive stars and AGB (Asymptotic Giant Branch) stars. Unfortunately, only a few of these radioactive nuclei are accessible to γ-ray astronomy. The main reason is that the emerging γ-ray lines from short-lived isotopes, however important their activity, might still be blocked in the stellar interiors and then inaccessible to observation, whereas the long-lived

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isotopes must be abundantly produced for their respective lines to be detectable. Therefore γ-ray telescopes which have been exploring this astronomical window for the last three decades usually deal with very low signal-to-noise ratio levels.

Most of these observable radioactive isotopes (*e.g.* ^{56}Ni, ^{57}Co, ^{60}Fe) are synthesised in SNe, either in core-collapse or thermonuclear explosions. Amongst them, ^{44}Ti is thought to be exclusively produced in those events. It emits three γ-ray lines with similar branching ratios at 67.9 and 78.4 keV (from ^{44}Sc*) and at 1.157 MeV (from ^{44}Ca*) during the decay ^{44}Ti $\longrightarrow$ ^{44}Sc $\longrightarrow$ ^{44}Ca with a weighted-average lifetime of 85.3 ± 0.4 yrs (see Ahmad et al., 2006, and references therein, for the recent ^{44}Ti lifetime measurements). Even though the production site of this element during the first stages of the explosion is still debated (Young et al., 2006), the region where the α-rich freeze-out from Si-burning at nuclear statistical equilibrium efficiently occurs is widely considered as the main location of ^{44}Ti production since the work of Woosley et al. (1973). Therefore, this isotope probes deep into the interior of these exploded stars, provides a direct way to study the SN-explosion mechanism itself, and represents the unique signature of any previously unknown young (*i.e.* few centuries old) supernova remnant (hereafter, SNR) as well.

As a consequence, ^{44}Ti production is strongly dependent on the explosion details, specifically on the mass-cut in core-collapse SNe (the mass above which matter is ejected), which is artificially defined in most of the theoretical models (Woosley & Weaver, 1995), the energy of the explosion, and the asymmetries (see *e.g.* Maeda, 2006) which have been revealed in several SNRs by recent optical and X-ray observations (Laming & Hwang, 2003; Fesen et al., 2006a). Moreover, the production of elements during the explosion is computed through a large nuclear network and therefore highly dependent on the nuclear cross sections of the implied reactions. It is of interest to point out that some of these nuclear reactions which govern the nucleosynthesis of ^{44}Ti (The et al., 1998) have been seriously revisited only recently (Sonzogni et al., 2000; Horoi et al., 2002; Nassar et al., 2006). It is therefore not surprising to see a large variation in the predicted theoretical ^{44}Ti yields, ranging from zero to a few 10^{-4} $M_{\odot}$ for the most frequent type II (Woosley & Weaver, 1995; Thielemann et al., 1996; Rauscher et al., 2002; Limongi & Chieffi, 2003) and type $I_{b/c}$ (Woosley et al., 1995) SNe, and up to 10^{-3}-10^{-2} $M_{\odot}$ for the rare event of the He-detonation of a sub-Chandrasekhar white dwarf (Woosley & Weaver, 1994; Livne & Arnett, 1995). As reported by Iwamoto et al. (1999), ^{44}Ti yields for standard type Ia SNe would lie between a few 10^{-6} and 5×10^{-5} $M_{\odot}$, in agreement with the improved multi-dimensional models of Travaglio et al. (2004) and Röpke et al. (2005).

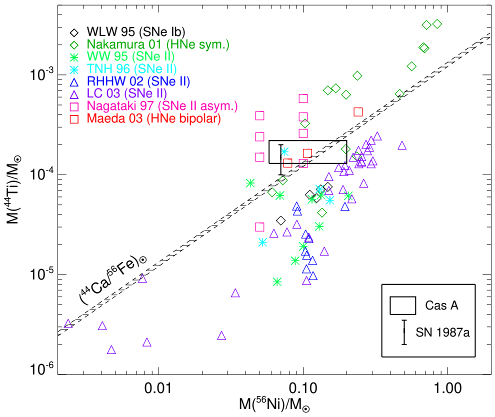

Fig. 1. ^{44}Ti yield versus ^{56}Ni yield diagram from models and observations for the case of core-collapse explosions. ^{56}Ni is supposed to be responsible for the early-time optical light-curve and is also thought to be produced in the innermost layers of the explosion. The black box and line represent the measurements (or estimates) of yields of these two nuclei in Cassiopeia A and SN 1987A, respectively. The different symbols refer to the main nucleosynthesis models. Only those which include asymmetries during the explosion would explain the high ^{44}Ti/^{56}Ni ratios observed in these SNRs. The dashed area corresponds to the solar ratio of the corresponding stable isotopes $(^{44}Ca/^{56}Fe)_{\odot}$ (Anders & Grevesse, 1989; Lodders, 2003).

Given these large uncertainties in the theoretical estimates, γ-ray observations turn out to be of great importance. The discovery of the 1157 keV ^{44}Ca γ-ray line emission in the youngest known Galactic SNR Cassiopeia A (hereafter, Cas A) with *CGRO*/COMPTEL (Iyudin et al., 1994) was the first direct proof that this isotope is indeed produced in SNe. This has been strengthened by the *BeppoSAX*/PDS detection of the two blended low energy ^{44}Sc lines at 67.9 keV and 78.4 keV (Vink et al., 2001). Recently, Renaud et al. (2006b) reported the detection of these two ^{44}Sc lines with the *INTEGRAL* IBIS/ISGRI instrument and calculated a weighted-average ^{44}Ti yield of 1.6 $^{+0.6}_{-0.3} \times 10^{-4}$ M$_{\odot}$. This high value, as compared to the theoretical predictions, could be due to several effects such as asymmetries (Vink, 2004; Hwang et al., 2004), as shown in Figure 1, and/or a high energy of the explosion (Laming & Hwang, 2003). Spectro-imaging measurements of these γ-ray lines would then bring unique information about the location and the dynamics of the ^{44}Ti emission regions. Moreover, Cas A appears to be the only SNR from which ^{44}Ti line emission has been unambiguously detected[1]. Therefore, a significant gain in sensitivity in the hard X-ray/soft γ-ray domain is also needed to address other sources of interest (listed by order of importance): SN 1987A, whose progenitor is known, and for which the same amount of ^{44}Ti as in Cas A is expected; Tycho and Kepler SNRs, most likely the remnants of type Ia SNe, from which no ^{44}Ti line emission has been detected so far; and the other ^{44}Ti-source candidates (*i.e.* young SNRs) that *INTEGRAL* IBIS/ISGRI and SPI and *SWIFT*/BAT will list at the end of their Galactic Plane surveys.

We present here the first simulations of the ^{44}Sc γ-ray lines at 67.9 and 78.4 keV, based on the spectro-imaging capabilities of *SIMBOL-X* (see the contributions of Ferrando et al. 2007, Pareshi et al. 2007 & Laurent et al. 2007 in these proceedings). *SIMBOL-X* will be the first formation flight mission whose payload is made of an optics module on a first spacecraft which focuses the radiation in the 0.5-100 keV energy range on two detectors nominally placed 20 m away on a second satellite. This mission will offer for the first time "X-ray"-like angular resolution ($\sim 18''$ HEW) and sensitivity (more than one order of magnitude better than IBIS/ISGRI up to $\sim$ 70 keV) in the hard X-ray domain.

[1] RX J0852-4622/GRO J0852-4642 (alias Vela Junior) might be the second SNR from which ^{44}Ti γ-ray line has been measured. Unlike Cas A, the detection originally claimed by Iyudin et al. (1998) with *CGRO*/COMPTEL is however still controversial (Schönfelder et al., 2000).

2. Simulations

In this contribution, we focus on the lower detection layer, a Cd(Zn)Te detector, operating between 5 and 100 keV, with a spectral resolution of the order of 1 keV (FWHM) at the ^{44}Sc line energies. All the simulations presented here were carried out with the generic set of response files provided by the organisers of the workshop.

2.1. Cas A: where is the ^{44}Ti ?

Cas A is the youngest known SNR in the Galaxy, located at a distance of $3.4^{+0.3}_{-0.1}$ kpc (Reed et al., 1995). The estimate of the supernova is A.D. 1671.3±0.9, based on the proper motion of several ejecta knots (Thorstensen et al., 2001). However, an event observed by Flamsteed (A.D. 1680) might be the origin of the Cas A remnant (Ashworth, 1980; Stephenson & Green, 2002). Even if it is generally accepted that Cas A was formed by the explosion of a massive progenitor (see *e.g.* Vink, 2004), there is still some debate on the detailed stellar evolution scenario (Young et al., 2006). The large collection of data from observations in the radio, infra-red, optical, X-ray (see *e.g.* Hwang et al., 2004) allows us to study its morphology, composition, cosmic-ray acceleration efficiency and secular evolution in detail. Most of this information has been inferred from recent X-ray observations which revealed a complex morphology of this SNR (Laming & Hwang, 2003), in particular a jet-counterjet structure in the Si-

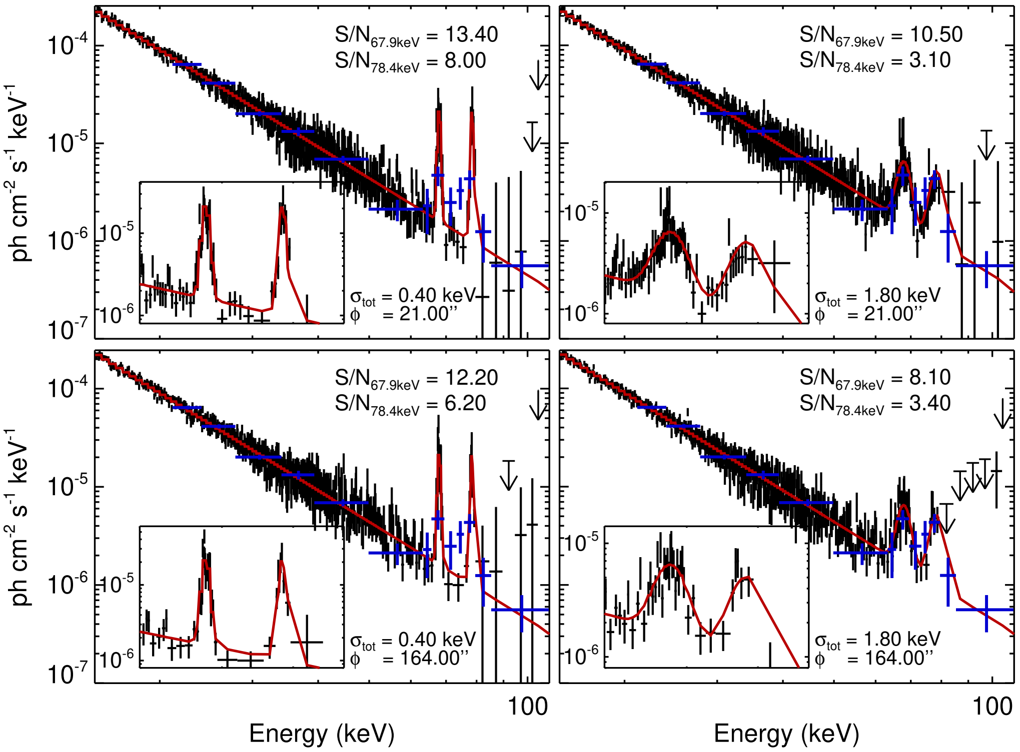

Fig. 2. Simulated spectra of Cas A based on the IBIS/ISGRI results for an exposure time of 100 ks with *SIMBOL-X* in four scenarios (in black). The case of an extended source ($\Phi = 164''$) correponds to an average velocity of 4000 km s^{-1} over 330 yrs at 3.4 kpc. The case of a broad line ($\sigma = 1.8$ keV) refers to an intrinsic velocity of $\sim$ 8500 km s^{-1}, as measured by Fesen et al. (2006b) in some fast-moving optical knots. Note that all of the signal-to-noise ratios were calculated over an interval of 1 keV centered on the lines. Upper limits are given at the 3 σ confidence level. For comparison, the IBIS/ISGRI data points from Renaud et al. (2006b) are superimposed in blue.

rich ejecta and several extremely Fe-rich regions (Hwang & Laming, 2003; Hwang et al., 2004). Highly Fe-rich ejecta are sites of complete Si burning in the explosion and may also harbor some of the ^{44}Ti known to have been synthesised in α-rich freezeout. Unfortunately, as pointed out by Hwang & Laming (2003), only "a few percent of the total Fe ejected by the explosion is currently visible in X-rays". Therefore, direct spatially-resolved spectroscopic measurements of the nucleosynthesis products through the observation of radioactive γ-ray lines would unambiguously reveal the composition of heavy nuclei and their dynamics.

In order to estimate the visibility of the ^{44}Sc γ-ray lines with *SIMBOL-X*, we assume a ^{44}Ti line flux of 2.5×10^{-5} cm^{-2} s^{-1} and a hard X-ray spectrum between 15 and 100 keV described by a power-law with an index Γ = -3.3, as recently measured by IBIS/ISGRI (Renaud et al., 2006b). Details about the nature of this continuum emission, which is related to the acceleration processes at the SNR forward shock, and the expectations with *SIMBOL-X* can be found elsewhere in these proceedings (Decourchelle et al. 2007). We further assume different scenarios. The most optimistic case is that of a static point-like source. The opposite corresponds to an extended source of 164″ in diameter (*i.e.* for an average velocity of 4000 km s^{-1} over 330 yrs at 3.4 kpc) with a current velocity of 8500 km s^{-1} (*i.e.* a line width of ∼ 1.8 keV at 70 keV), as observed in some optical knots (Fesen et al., 2006b). Figure 2 shows the simulated Cas A spectra for a 100 ks observation with *SIMBOL-X* (in black), in comparison with the IBIS/ISGRI data points (in blue). Even in the worst case of an high-velocity extended source, both ^{44}Sc lines would be clearly detected by *SIMBOL-X* for this reasonable exposure time. Moreover, from the spectral fit, we have estimated a 3 σ Doppler-velocity resolution of the order of (2000-2800) km s^{-1} at 67.9 keV and (4000-4500) km s^{-1} at 78.4 keV, *i.e.* well below the current forward shock velocity of ∼ 5200 km s^{-1} (Vink et al., 1998). This would allow us to obtain for the first time unique information on the dynamics of the nucleosynthesis sites which occurred close to the mass-cut during the first stages of the explosion.

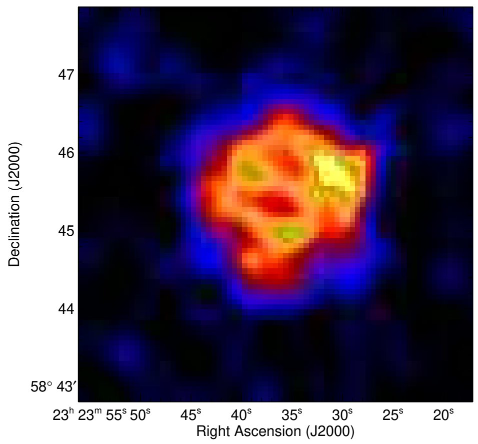

Fig. 3. Simulated image of Cas A with *SIMBOL-X* assuming a uniform distribution of ^{44}Ti within a 82″ radius sphere and with a global weighted-average line flux measured by Renaud et al. (2006b). To improve the visibility of this low statistics image, a 20″ Gaussian smoothing has been applied. At this scale, the *SIMBOL-X* PSF (HEW) is five sky pixels.

We have also estimated the imaging capabilities of *SIMBOL-X* by simulating a uniform distribution of ^{44}Ti (note that this would represent the worst case of detectability) over a 82″ radius sphere. The resulting image is shown in Figure 3, on which we applied a 20″ Gaussian smoothing (FWHM). *SIMBOL-X* should then be able to disentangle amongst several plausible scenarios of asymmetries originated from the explosion such as a jet-counterjet structure or a clumpy distribution.

2.2. SN 1987A: how much ^{44}Ti has been synthesised in the explosion of a known massive star ?

SN 1987A is unique because it is the only case for which the progenitor star is known. Sanduleak -69°202 was initially a red supergiant of ∼ 20 $M_\odot$ (Podsiadlowski, 1992) and produced a dense, slow, wind focused into the equatorial plane of the system. The star then evolved into a blue supergiant and began to produce a high-velocity, low-density, isotropic wind. However, the details of its late-time evolution are still not completely clear (Smith, 2007), and the presence of a triple-ring optical nebula around SN 1987A could be due to the merger of two massive stars 20,000 yrs prior to the explosion (Morris & Podsiadlowski, 2007). It now represents a unique laboratory for studying the interaction between the circumstellar medium of a massive star and the SN ejecta in the radio and X-ray domains (Gaensler et al., 2007).

The γ-ray lines originated from the decay of ^{56}Co (Matz et al., 1988; Tueller et al., 1990) and ^{57}Co (Kurfess et al., 1992) which are supposed to feed the early-time bolometric light-curve have been detected from SN 1987A. The current light-curve is thought to be powered by the radioactive decay of ^{44}Ti. A precise measurement of its γ-ray lines would therefore be invaluable for constraining the models of massive star evolution and explosive nucleosynthesis (through the ^{44}Ti/^{56}Ni ratio, as shown in Figure 1). From Monte-Carlo simulations of Compton degradation of γ-ray photons in the SN ejecta, Motizuki & Kumagai (2004) have found a yield of (0.8-2.3) × 10^{-4} $M_{\odot}$ of ^{44}Ti to be required to power the observed light-curve. This value is in a good agreement with the modeling of the infrared emission lines of the ejecta (Fransson & Kozma, 2002). Such a yield, comparable to that measured in Cas A, would produce a ^{44}Ti line flux from SN 1987A (4-12) times weaker than that measured in the former. Therefore, a 10^6 s *SIMBOL-X* observation should lead to the detection of the 67.9 and 78.4 keV ^{44}Sc lines at ~ 6 and 4 σ, respectively in the worst case (smaller yield).

2.3. Tycho & Kepler SNRs: ^{44}Ti yields and nature of the explosions

The Tycho (SN 1572) and Kepler (SN 1604) SNRs are the remnants of famous historical Galactic SNe. The stellar explosions have been observed by several astronomers, from China, Korea and Europe. Nowadays, both remnants are studied in details through observations in the radio and X-ray domains. However, many questions still remain unanswered.

Kepler's progenitor is somewhat of an enigma. The light-curve obtained by Koreans and Johannes Kepler suggests a type Ia event with an absolute magnitude M_V ~ -18.8 at the peak (Stephenson & Green, 2002), and its distance far above the Galactic Plane, > 500 pc at a distance of 4.8 kpc (Reynoso et al., 1999), also supports this hypothesis. Moreover, Kinugasa & Tsunemi (1994) have measured from *ASCA* observations a relative overabundance of iron that agrees with type Ia nucleosynthesis models. However, the nitrogen overabundance in the optical knots (Dennefeld, 1982), the slow expansion velocities of these knots and the enhanced density in the region suggest that there is circumstellar material ejected by the stellar wind from a massive star. Bandiera (1987) has then proposed a model suggesting that the progenitor was a massive "runaway star" ejected from the Galactic Plane. Recent *Chandra* observations have confirmed the prominence of iron emission, together with the absence of O-rich ejecta, making the scenario of a type Ia SN progenitor with a circumstellar interaction more likely (Reynolds et al., 2007). Tycho is considered as the prototype of a type Ia SN (Baade & Minkowski, 1954). With an age of 435 yr and a distance of 2.3 ± 0.8 kpc (Smith et al., 1991), this SNR is the most promising candidate to observe explosive nucleosynthesis products from a thermonuclear SN. Decourchelle et al. (2001) and Hwang et al. (2002) have studied through *XMM-Newton* and *Chandra* observations the composition and the structure of the ejecta. Similarly to Kepler SNR, Si and Fe-rich ejecta knots have been found and both integrated X-ray spectra look alike, although Tycho would be the result of a convential type Ia encountering low-density, more or less uniform ISM.

No ^{44}Ti γ-ray line has ever been detected in these two SNRs so far. Only upper limits from Tycho were reported with IBIS/ISGRI (Renaud et al., 2006c), from which sub-Chandrasekhar models have been ruled out. Unfortunately, these measurements did not permit to check the validity of the standard models. High sensitivity observations of these two SNRs in the soft γ-ray domain would then bring either a detection or strong constraints on nucleosynthesis models in standard type Ia SNe. In the case of Tycho, Badenes et al. (2003) have considered the possibility to efficiently constrain the nature of the progenitor through a careful analysis of the SNR thermal X-ray spectrum. They have estimated a ^{44}Ti yield of about 6 × 10^{-6} $M_{\odot}$. If one assumes such value for both Tycho and Kepler SNRs, this would imply a ^{44}Ti line flux of ~ 5 and 2 × 10^{-5} cm^{-2} s^{-1}, respectively. Since these are roughly the same as those expected from SN 1987A, a deep observation with *SIMBOL-X* (~ 10^6 s) would be required[2].

2.4. Search for Galactic "young, missing and hidden" SNRs: ^{44}Ti production and SNe rate

The last topic that *SIMBOL-X* would be in a position to study concerns the search for young

[2] Note that, unlike SN 1987A, the non-negligible size of Tycho and Kepler SNRs (8 and 3′, respectively) may require a few pointings to map them and an increase of the observing time.

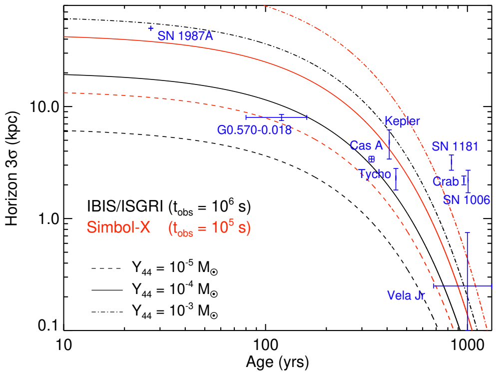

Fig. 4. The 3 σ sensitivity, expressed as the distance at which a SNR would be detected at this significance level (called horizon, in units of kpc), of IBIS/ISGRI (black lines, for an exposure time of 10^6 s) and *SIMBOL-X* (red lines, for an exposure time of 10^5 s) as a function of the SNR age, for ^{44}Ti yields of 10^{-5} (dashed), 10^{-4} (solid) and 10^{-3} $M_{\odot}$ (dot-dashed). The historical SNRs are also indicated with their respective uncertainties on the distance and age (Green, 2005). Note that any SNR is considered as a point-like source for both instruments in this calculation (which is not the case for historical Galactic SNRs at the scale of the *SIMBOL-X* PSF). G0.570-0.018 is a young SNR-candidate suggested by Senda et al. (2002).

and previously unknown Galactic SNRs. Since four centuries and Kepler's SN, no stellar explosion has been optically observed, while 2-3 such events are expected per century in the Milky Way (see *e.g.* Cappellaro et al., 1999). The reason is that most of the SNe occurred in highly obscured regions and therefore remain undetected. One way to avoid such a limitation is to search for ^{44}Ti γ-ray lines, exempt from interstellar extinction. Moreover, 2-3 Cas A/SN 1987A-like ^{44}Ti events per century are required to explain the current Galactic ^{44}Ti production rate deduced from the observed solar ^{44}Ca abundance through the common Galactic chemical evolution models (see The et al., 2006, and references therein). However, several γ-ray line surveys (Mahoney et al., 1992; Leising & Share, 1994; Dupraz et al., 1997; Renaud et al., 2004; The et al., 2006) have highlighted the problem of the lack of solid ^{44}Ti-source candidates / young SNRs (except Cas A), those that should have occurred since Cas A and are still not detected through the line emission from ^{44}Ti decay. The et al. (2006) have then raised the question of the exceptionality of ^{44}Ti-producing SNe.

Even if no serious candidate has emerged yet, significant detections are expected with the continuous improvement of the IBIS/ISGRI survey sensitivity before the launch of *SIMBOL-X*. The relatively narrow field of view of *SIMBOL-X* will not permit a survey of the Galaxy in the ^{44}Ti γ-ray lines as that performed with *INTEGRAL*. On the other hand, dedicated observations will allow a gigantic step forward in sensitivity. Figure 4 illustrates this purpose and shows the 3 σ sensitivity, expressed as the distance at which a SNR would be detected at this significance level, of IBIS/ISGRI (for an exposure time of 10^6 s) and *SIMBOL-X* (for an exposure time of 10^5 s) as a function of the SNR age for different ^{44}Ti yields. As an example, G0.570-0.018 is a SNR-candidate close to the Galactic Center that might be as young as ~ 100 yr (Senda et al., 2002). Even if IBIS/ISGRI upper limits on the ^{44}Ti line flux and the non-detection of radio emission brought severe constraints on the nature of this source (Renaud et al., 2006a), *SIMBOL-X* should be able to detect it for ^{44}Ti yields down to ~ 10^{-5} $M_{\odot}$. Therefore, confirming these young Galactic SNR-candidates, measuring precisely ^{44}Sc line fluxes and their Doppler-velocity, and mapping the emission turn out to be tasks that only *SIMBOL-X* can tackle.

3. Conclusion

SIMBOL-X will undoubtedly play a major role in our understanding of the explosive nucleosynthesis processes through the ^{44}Ti radioactive γ-ray lines from young Galactic SNRs. Thanks to its spectro-imaging capabilities and sensitivity, it will allow us to locate precisely the ^{44}Ti-emitting regions and to measure their velocity in Cas A for the first time. The detection of these γ-ray lines in SN 1987A will greatly constraint the models of evolution of massive stars and nucleosynthesis processes.

Moreover, it might detect them in other SNRs such as Tycho and Kepler, whose progenitors are still a matter of debate. The issue of the sources at the origin of the Galactic ^{44}Ca will also be adressed by *SIMBOL-X* through dedicated observations of young SNR-candidates that wide-field instruments like those onboard *INTEGRAL* should reveal.

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