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ASTRONOMY
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COMPTEL three-year search for Galactic sources of ^{44}Ti gamma-ray line emission at 1.157 MeV

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Abstract. Because of its short lifetime, radioactive ^{44}Ti is a probe of the supernova activity of the Galaxy during the last few centuries. The COMPTEL experiment aboard the Compton Observatory is capable of imaging sources of ^{44}Ti line emission at 1.157 MeV with a sensitivity of about $2\,10^{-5}\,\gamma\,\mathrm{cm^{-2}\,s^{-1}}$. The latest known supernova remnant in the Milky Way, Cassiopeia A, has already been detected by COMPTEL (Iyudin et al. 1994). Although no further event has been observed for 300 years, young objects still obscured by interstellar extinction may also show up in the light of decaying ^{44}Ti.

Using the first three years of COMPTEL observations, we have carried out a systematic 1.157 MeV survey of the Galactic plane in order to search for these conjectural ^{44}Ti sources. We report on the following issues:
— of the six Galactic supernovae recorded during the last millenium, *only Cassiopeia A is detected by COMPTEL*. The updated flux, $(3.4 \pm 0.9)\,10^{-5}\,\gamma\,\mathrm{cm^{-2}\,s^{-1}}$ (systematic uncertainty $\lesssim 25\%$), is lower than previously determined and implies an initial ^{44}Ti mass of 0.9 to $2.4\,10^{-4}\,\mathrm{M_\odot}$ in better agreement with observational and theoretical pictures of the Cas A supernova;
— *no serendipitous ^{44}Ti source is detected by COMPTEL at the $\geq 3\,\sigma$ level*, whereas we would expect 3 detections on statistical grounds. This negative conclusion is consistent at the $< 5\%$ confidence level with canonical values of the Galactic supernova rate (2.5 to 3 events per century) and ^{44}Ti supernova yields (a few 10^{-5} to $10^{-4}\,\mathrm{M_\odot}$).

Key words: nucleosynthesis – gamma-ray: observations – supernovae: general – ISM: supernova remnants

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1. Introduction

Gamma-ray line spectroscopy is one of the main observational goals of the COMPTEL experiment aboard NASA's Compton Gamma-Ray Observatory (CGRO) (Schönfelder et al. 1993). In particular, several radioactive products of stellar nucleosynthesis generate line emission in the 0.75–30 MeV energy range covered by this instrument (see Diehl 1995). For the first time, the celestial 1.809 MeV line emission from ^{26}Al decay has now been mapped by COMPTEL (Diehl et al. 1995, Oberlack et al. 1996).

^{44}Ti is another radio-isotope of astrophysical interest. As already stressed long ago (Bodansky, Clayton & Fowler 1968), it is the sole parent of natural ^{44}Ca. The rate of ^{44}Ti nucleosynthesis and supernova explosions sets the Galactic abundance of this species (Clayton 1982, Woosley 1993). Radioactive ^{44}Ti decays into stable ^{44}Ca via ^{44}Sc:

$$^{44}\mathrm{Ti} \xrightarrow[\tau\,\sim\,85\,\mathrm{yr}]{67.9\,\mathrm{keV},78.4\,\mathrm{keV}} {}^{44}\mathrm{Sc} \xrightarrow[\tau\,=\,8.2\,\mathrm{hr}]{1.157\,\mathrm{MeV}} {}^{44}\mathrm{Ca}\,.$$

The mean lifetime of ^{44}Ti is still uncertain. Values of τ as different as 78.2 yr (Frekers et al. 1983) and 96.1 yr (Adelberger & Harbottle 1990) have been proposed. More recent measurements, yet preliminary, encompass this range with $\tau = 84 \pm 14$ yr (Meißner et al. 1995).

Supernovae are the site of ^{44}Ti nucleosynthesis through explosive Si burning (see Hoffman et al. 1995, Timmes et al. 1996 for reviews). Production is most efficient within an alpha-rich freeze-out of nuclear statistical equilibrium, at low densities. This process operates in core-collapse events (Woosley, Arnett & Clayton 1973, Thielemann, Hashimoto & Nomoto 1990), while a normal freeze-out Si burning is rather at play in Type-Ia objects (Thielemann, Nomoto & Yokoi 1986). The amount of ^{44}Ti ejected by the supernova depends on the mechanism of explosion and the progenitor mass and metallicity. It is quite sensitive to the mass cut between the remnant and the ejecta, i.e. to how much mass falls back onto the core. Different models of core-collapse supernovae predict values of the yield Y_{44} between a few 10^{-5} and 10^{-4} $M_\odot$ (e.g. Woosley & Weaver 1995, Woosley, Langer & Weaver 1996, Thielemann, Nomoto & Hashimoto 1996), while the Type-Ia model of Nomoto, Thielemann & Yokoi (1984) only produces $1.8\,10^{-5}$ $M_\odot$ of ^{44}Ti.

In contrast with the slow decay of ^{26}Al ($\sim 10^6$ yr), the lifetime of ^{44}Ti is rather short. While 1.809 MeV emission regions must be due to an ensemble of sources as a result of ^{26}Al accumulation in the interstellar medium over several million years (Diehl et al. 1996), only fairly recent, rather nearby, individual explosive events are detectable through their ^{44}Ti afterglow. The daughter ^{44}Sc line at 1.157 MeV probes the *supernova activity of the Galaxy within the last few centuries*. It was amongst the first predicted gamma-ray diagnostics of young supernova remnants (SNR s hereafter) (Clayton, Colgate & Fishman 1969).

Due to the lack of spatial resolution, previous gamma-ray spectroscopy experiments only put constraints on the *global Galactic emission* in the lines associated with ^{44}Ti decay. Using HEAO 3, Mahoney et al. (1992) give an upper limit of $2\,10^{-4}\,\gamma\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ for the 67.9 and 78.4 keV lines at the 99% confidence level. Measurements by SMM provide a more stringent limit: the 1.157 MeV flux from the inner 150° of the Milky Way cannot exceed $0.8\,10^{-4}\,\gamma\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ at a similar level (Leising & Share 1994).

Because of its better sensitivity and spatial resolution, COMPTEL is suited for a systematic survey of the Galaxy in the 1.157 MeV line. Cassiopeia A, the youngest known Galactic SNR, has already been detected by COMPTEL (Iyudin et al. 1994) with a flux of about $7\,10^{-5}\,\gamma\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. Further analysis of more data however points to a slightly lower value, $(4.2 \pm 0.9)\,10^{-5}\,\gamma\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ (Schönfelder et al. 1996). At first, this result was not confirmed by OSSE onboard the Compton Observatory (The et al. 1995). More recently, a marginal detection was reported by The et al. (1996) with a ^{44}Ti line flux of $(1.7 \pm 1.4)\,10^{-5}\,\gamma\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. Within $1\,\sigma$ uncertainties, the latest COMPTEL and OSSE determinations are in agreement.

In the present work, we combine the first three years of COMPTEL data (Sect. 2) in order to carry out a complete search of the Galactic plane for ^{44}Ti sources (Sect. 3). The purpose of this survey is twofold:

- A systematic study of historical supernovae (Sect. 4). Astronomical records list only six objects in the second millenium (van den Bergh & Tammann 1991). SNR s associated with these recent nearby events are obviously potential sources of 1.157 MeV line emission. We give constraints on the ^{44}Ti yields of the progenitors.
- A search for young Galactic SNR s (Sect. 5). A rate of 2.5 events per century is estimated for the Milky Way (Tammann, Löffler & Schröder 1994). Possibly hidden by local interstellar extinction, recent supernovae may be probed today by their ^{44}Ti line emission.

2. Observations and analysis apparatus

2.1. The instrument

The COMPTEL telescope was designed to detect gamma-ray photons in the 0.75–30 MeV range with an energy resolution of 6–10% (FWHM). Within a field of view of about 1 steradian, it is able to locate gamma-ray sources with a spatial accuracy of 1° typically. A detailed description of the instrument and the detection principle are presented by Schönfelder et al. (1993). Ideally, incoming photons are first Compton scattered in an upper detector layer, then completely absorbed in a lower detector layer. The energy deposits and locations in these layers determine the scatter direction, scatter angle, and total energy of each photon. Events are sorted in a 3D dataspace defined by the scatter direction (χ, ψ) and Compton scatter angle $\bar{\varphi}$.

The CGRO observation programme consists of several successive phases. The present work involves all observations of the Galaxy from 16 May 1991 to 4 October 1994 (Phases I to III as listed by Gehrels et al. 1994). We specifically combined the ~ 75 viewing periods with the telescope pointing within 35° from the Galactic plane, of durations of typically 10^6 s each. The 3D dataspace spans a total of $360° \times 120° \times 50°$ in $(\chi, \psi, \bar{\varphi})$, respectively, and the events are binned in $1° \times 1° \times 2°$ cells.

2.2. Data reduction and background models

The detection of celestial gamma-ray emission involves the identification of source signatures in the 3D dataspace. We have generated a map of the Galactic plane at 1.157 MeV by applying a *maximum-likelihood* method to the data (de Boer et al. 1992). This algorithm is very appropriate to a search for ^{44}Ti sources. Testing indeed for the presence of point sources throughout the map, it gives flux estimates and statistical significances of such sources (Sect. 2.3). For comparison, we also generated maximum-likelihood maps for two neighbouring energy bands. We thus prepared 3D datasets for the following energy intervals: 0.89–1.07 MeV, 1.07–1.25 MeV, and 1.25–1.43 MeV, where the middle one is centered on the ^{44}Ti line. This narrow bandwidth takes full advantage of the energy resolution of the instrument (σ = 45 keV at 1.157 MeV). Selections in time of flight (channels 115–130) and pulse shape (channels 0–110) are applied for rejection of backward-scattered photons and neutron events, respectively (Schönfelder et al. 1993).

Proper description of the background is critical, as the signal is not expected to exceed 1% of the total number of events. We have achieved background modelling within the 3D dataspace in two different ways:
(i) data from neighbouring energy bands are interpolated, taking into account the specific variations of the different dataspace variables with energy (Knödlseder et al. 1996);
(ii) data from the same observations and energy range are filtered with a smoothing technique similar to that described by Bloemen et al. (1994).

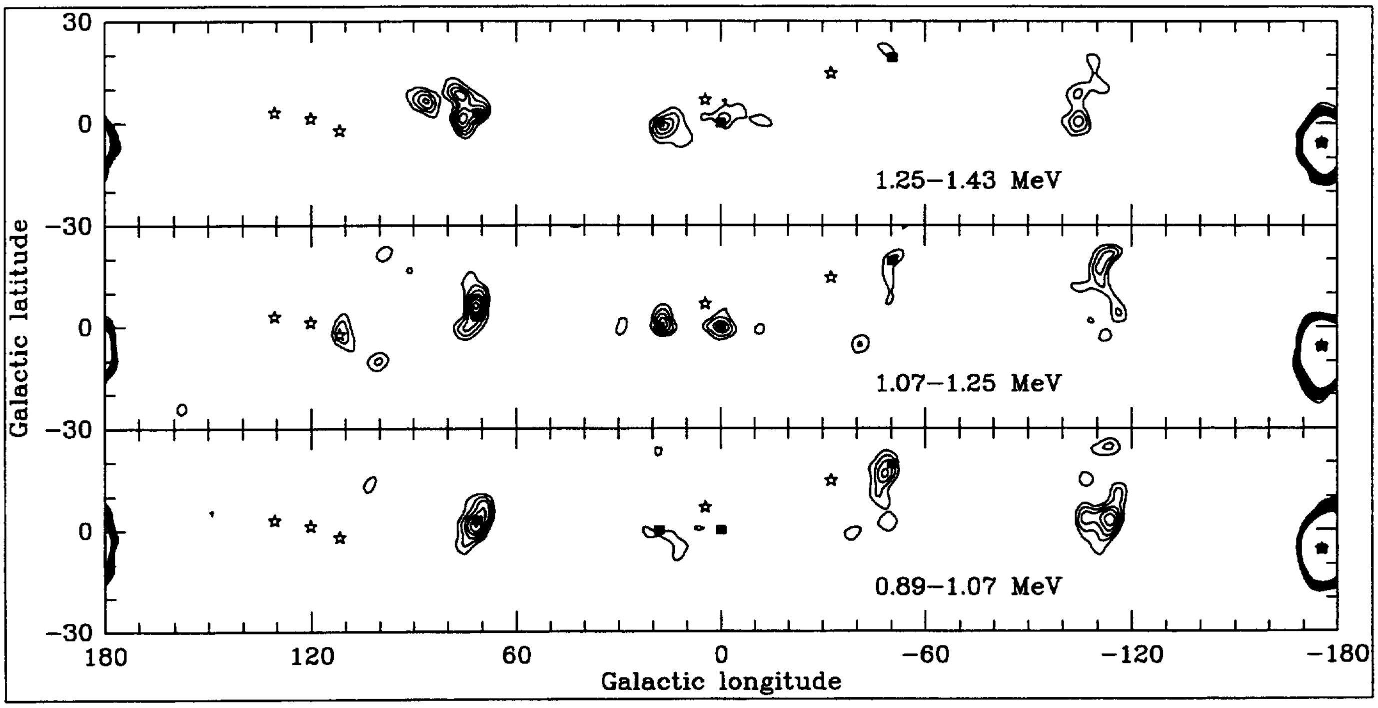

Fig. 1. Maximum-likelihood maps of the Galactic plane in three energy bands: 0.89–1.07 MeV (*bottom*), 1.07–1.25 MeV (*middle*), 1.25–1.43 MeV (*top*). The contours start at $-2\ln\lambda = 6$ with steps of 3. The central map includes ^{44}Ti line emission at 1.157 MeV. Continuum sources are indicated by filled squares (Table 1). Stars show historical SNRs from the last millenium (Table 2).

In principle, method (i) includes any continuum contribution in the background so that mainly line emission is imaged. In contrast, method (ii) makes no discrimination and images the total (line + continuum) celestial emission.

2.3. *The significance of source detections*

For each pixel of the sky image, the *maximum-likelihood ratio* λ is calculated as the ratio between the likelihood of the best fit to the data by the background model alone to that of the best fit including a point source at this position: $\lambda = L_{\max}(\text{background})/L_{\max}(\text{source} + \text{background})$. The quantity $-2\ln\lambda$ measures the statistical significance of the presence of a point source at the pixel location.

In the process of identifying known celestial objects as possible sources, $-2\ln\lambda$ follows a χ^2 *distribution with one degree of freedom*: the source flux. For example, a value of $-2\ln\lambda = 9.0$ would indicate that the object is detected in the gamma-ray band at the $3\,\sigma$ significance level.

A higher threshold is required in a search for previously unknown sources since $-2\ln\lambda$ now obeys a χ^2 *distribution with three degrees of freedom*: source flux and coordinates. A $3\,\sigma$ confidence level implies $-2\ln\lambda = 14.4$. However this figure stems from a *local optimisation* with no account of the *large sky area* scanned by COMPTEL (Schönfelder et al. 1993). We require $-2\ln\lambda > 16.5$ ($> 3.3\,\sigma$) in order to claim a serendipitous source detection: at this level, $\lesssim 0.2$ spurious excesses are expected to show up in our map.

3. Propædeutics to the ^{44}Ti line analysis

3.1. *A view to the Galaxy at* 1.157 *MeV*

We first use background method (ii) in order to image the full celestial emission. Figure 1 shows likelihood maps of the Galactic plane in the narrow energy bands of Sect. 2.2. A striking feature of these maps is their relative emptiness, with only a few localised excesses. In contrast, COMPTEL all-sky images in the 1–3, 3–10, and 10–30 MeV ranges (see Schönfelder et al. 1996) display a ridge of emission along the Galactic plane, probably due to point-like sources and a diffuse component (e.g. Bloemen et al. 1994, Strong et al. 1994). Low statistics probably explains the difference: the extended emission of the Milky Way may remain below the sensitivity level achieved in narrow energy bands.

Line studies require that the underlying continuum be suppressed. Background method (i) was developed to this aim and applied to the analysis of Galactic ^{26}Al emission at 1.809 MeV (Diehl et al. 1995). However the ^{44}Ti line is closer to the energy threshold of COMPTEL below 1 MeV, which makes more difficult an estimation of the continuum level from adjacent energies. We thus keep method (ii) and check *any significant excess* in the 1.07–1.25 MeV map of Fig. 1. Line emission can be assessed with respect to the neighbouring 0.89–1.07 and 1.25–1.43 MeV measurements. This choice ensures that we miss no potential ^{44}Ti source. Consistency checks between methods (i) and (ii) establish that systematic effects should not be in excess of 25%.

Table 1. Characteristics of the five continuum sources detected by COMPTEL in the 1.07–1.25 MeV band (Fig. 1). Fluxes are given in this band and two adjacent energy intervals together with their formal 1 σ uncertainty. An $E^{-2.0}$ power-law spectrum is assumed when deriving these values. Most detections are at the > 3 σ significance level in all three bands.

Source name	Coordinates		Flux ($10^{-4}\,\gamma\,\mathrm{cm^{-2}\,s^{-1}\,MeV^{-1}}$) in band		
	l_{gal}	b_{gal}	0.89–1.07 MeV	1.07–1.25 MeV	1.25–1.43 MeV
"Galactic Centre excess"	0.00	0.00	0.96 ± 0.49	1.71 ± 0.39	1.19 ± 0.35
"$l = 18$ source"	18.00	0.00	1.42 ± 0.49	1.77 ± 0.39	1.70 ± 0.35
Cygnus X–1	71.33	+3.07	3.13 ± 0.58	2.39 ± 0.46	1.84 ± 0.41
Crab	184.56	−5.78	19.6 ± 0.58	15.3 ± 0.49	10.7 ± 0.42
Centaurus A	309.52	+19.42	2.20 ± 0.58	1.62 ± 0.47	1.23 ± 0.42

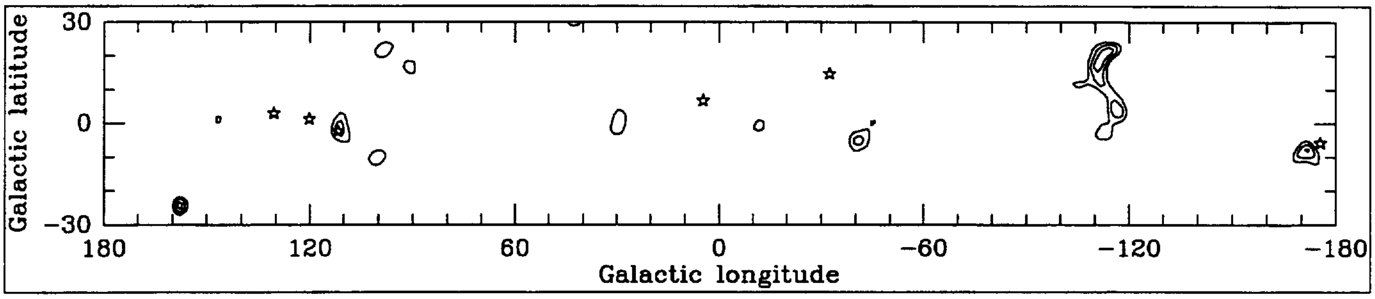

Fig. 2. Residual map of the Galaxy in the energy band 1.07–1.25 MeV. This likelihood map is similar to Fig. 1, except that the continuum sources of Table 1 were included in the background model, thus excluded from the search for ^{44}Ti sources. Contours start at $-2\ln\lambda = 6$ with steps of 3. Stars indicate historical SNRs from the second millenium (Table 2). Continuum emission may account for the elongated feature at $l \sim 250°$ (Sect. 3.2). The excess close to the Crab seems consistent with the continuum source (active galactic nucleus) PKS 0528+134 at $l = 191.37°$, $b = -11.01°$ (Collmar et al. 1994).

3.2. Continuum sources in the 1.157 *MeV sky*

A small number of excesses (Table 1) show up in all three maps of Fig. 1 and can be identified as continuum gamma-ray sources (see Schönfelder et al. 1996 for a review):

- the Crab is by far the most intense celestial source in the MeV regime (Much et al. 1995). It is detected with $-2\ln\lambda$ of several hundreds in our narrow bands.
- the X-ray binary/black-hole candidate Cygnus X–1 is the second strongest source in our maps (McConnell et al. 1994).
- hosted by a peculiar elliptical galaxy, NGC 5128, Centaurus A is the closest active galactic nucleus detected by COMPTEL (Steinle et al. 1995).
- a strong source shows up at $l \sim 18°$, $b \sim 0°$. It coincides with a feature seen in the COS B data (Bloemen 1989) but is still unidentified.
- emission is detected towards the Galactic Centre with a flux in the 1.07–1.25 MeV range which is larger than in adjacent energy bands. This excess may well belong to the extended ridge of Galactic diffuse emission.

At $l \sim 250°$, there is evidence for an extended feature also visible in broad-band 1–3 MeV images.

We discard these continuum sources by including them in the background model with fluxes as given in Table 1. The feature towards the Galactic Centre deserves special attention. The band-to-band variations are within the 2 σ level and yield no evidence for significant 1.157 MeV line emission. From measurements in our neighbouring bands, we assign a 1.07–1.25 MeV flux of $10^{-4}\,\gamma\,\mathrm{cm^{-2}\,s^{-1}\,MeV^{-1}}$ to the underlying continuum.

We then repeat the maximum-likelihood analysis and build the residual likelihood map of Fig. 2.

4. The ^{44}Ti line emission of historical supernovae

4.1. Interpretation of COMPTEL results

Due to the short lifetime of radioactive ^{44}Ti, young SNRs are the best potential sources of 1.157 MeV line emission. The history of astronomy records six supernova events in the course of the second millenium (van den Bergh & Tammann 1991). For each SNR, the maximum-likelihood analysis provides a flux estimate $F_{1.157}$ and $-2\ln\lambda$ quantifies the confidence level for a source detection (Table 2).

Let D (kpc) denote the distance to the SNR, Y_{44} ($\mathrm{M_\odot}$) the ejected mass of ^{44}Ti, and t (yr) the time elapsed since the explosion. If τ is the mean ^{44}Ti lifetime, the 1.157 MeV flux expected to be measured today reads:

$$F_{1.157} = 7200\,\gamma\,\mathrm{cm^{-2}\,s^{-1}} \times \frac{Y_{44}}{D^2} \times \frac{e^{-t/\tau}}{\tau}. \quad (1)$$

Table 2. COMPTEL measurements of ^{44}Ti line emission from Galactic supernovae of the second millenium. Supernova distances and types are gathered from van den Bergh (1990). An explosion date of 1680 is assumed for Cas A (Fesen, Becker & Goodrich 1988) according to Flamsteed's testimony (Ashworth 1980). From the 1.157 MeV line fluxes and upper limits, two estimates of the ^{44}Ti yield are inferred depending on the ^{44}Ti lifetime (Sect. 1). Formal $1\,\sigma$ uncertainties are given for Cas A; upper limits are quoted at the $2\,\sigma$ confidence level. Systematic uncertainties are estimated to be less than 25%. No line flux is reported for the Crab which is a strong continuum source. Since its progenitor was a $9\,M_\odot$ star (Nomoto et al. 1982), SN 1054 released less than $10^{-4}\,M_\odot$ of ^{44}Ti (Woosley & Weaver 1995) so that the present-day flux is more than a hundred times below the sensitivity threshold of COMPTEL. A search for gamma-ray lines from the Crab is currently underway (van der Meulen et al. 1996).

Supernova name	Year	Type	Coordinates l_{gal}	b_{gal}	Distance (kpc)	Likelihood $-2\ln\lambda$	1.157 MeV flux ($10^{-5}\,\gamma\,cm^{-2}\,s^{-1}$)	^{44}Ti yield ($10^{-4}\,M_\odot$) for $\tau = 96.1$ yr	$\tau = 78.2$ yr
Kepler SN	1604	Ib/II?	4.52	+6.84	4.2	0.0	≤ 1.43	≤ 2.0	≤ 4.0
Cassiopeia A	~1680	Ib	111.74	−2.13	~ 3.0	12.1	3.4 ± 0.9	1.1 ± 0.3	1.8 ± 0.5
Tycho SN	1572	Ib?	120.09	+1.42	2.5	1.2	≤ 1.78	≤ 1.2	≤ 2.7
3C58	1181 ?	II?	130.72	+3.08	2.6	0.7	≤ 1.78	≤ 75	≤ 430
Crab SN	1054	II	184.56	−5.78	2.0	—	—		
Lupus SN	1006	Ia	327.51	+14.64	1.4	0.1	≤ 1.50	≤ 120	≤ 980

At present, τ is loosely determined between 75 yr and 95 yr (Sect. 1). Rather than assuming any arbitrary lifetime, we convert each COMPTEL flux into two ^{44}Ti yields according to the values of τ proposed by Adelberger & Harbottle (1990) and Frekers et al. (1983):

$$\begin{aligned} \tau = 96.1\,\mathrm{yr} &\longrightarrow Y_{44} = F_{1.157}\,D^2 \times 0.0133\; e^{t/96.1} \\ \tau = 78.2\,\mathrm{yr} &\longrightarrow Y_{44} = F_{1.157}\,D^2 \times 0.0108\; e^{t/78.2} \end{aligned} \quad (2)$$

(Table 2). The inaccurate knowledge of τ translates into a large uncertainty on Y_{44}. For a 400 yr old supernova, these yield estimates differ by a factor of two.

Out of the six historical supernovae recorded in the last millenium, only Cassiopeia A is detected by COMPTEL. Upper bounds of $F_{1.157} \sim 1.8\,10^{-5}\,\gamma\,cm^{-2}\,s^{-1}$ are derived for the other objects at the $2\,\sigma$ confidence level. Whether this actually constrains the Y_{44} yields depends on the SN event date. Supernovae from the 11th and 12th centuries – SN 1006 (Lupus), SN 1054 (Crab), SN 1181 (3C58) – are much too old. Upper limits of $Y_{44} \sim 10^{-2}\,M_\odot$ appear well above nucleosynthesis predictions by any standard model (Sect. 1). In the following we only discuss the three 16th- and 17th-century supernovae.

4.2. SN 1572 and SN 1604

From its low brightness and the shape of its light curve, SN 1572 (Tycho's SN) is classified as a Type-Ib supernova (Strom 1988). Type II-L is not excluded however (Doggett & Branch 1985) while van den Bergh (1993) even suggests that it may be a subluminous Type-Ia supernova. SN 1604 (Kepler's SN) is of equally uncertain type (van den Bergh 1990). Its high Galactic latitude favours a progenitor from the old stellar population (SN Ia), but the core collapse of a massive 'runaway star' (Bandiera 1987) now seems more plausible (Bandiera & van den Bergh 1991).

Our results set marginal constraints on the ^{44}Ti mass released by these supernovae. If distance uncertainties are taken into account, $D \sim 2.5$ kpc (Strom 1988) to 4.5 kpc (Schwarz et al. 1995) for SN 1572 and 3–5 kpc (Rothenflug et al. 1994) for SN 1604, our observations imply ^{44}Ti yields of $Y_{44} \lesssim 1\text{–}5\,10^{-4}\,M_\odot$. These values are tantalizingly close to model predictions (Sect. 1; see Fig. 3), which suggests that both SN 1572 and SN 1604 are potential targets for the planned INTEGRAL mission in the 1.157 MeV line or for operational X-ray missions (XTE and SAX) in the two ^{44}Ti lines at 67.9 and 78.4 keV, with fluxes in the range 10^{-6} to $10^{-5}\,\gamma\,cm^{-2}\,s^{-1}$.

4.3. Cassiopeia A

Cas A is considered to be a Type-Ib supernova involving a Wolf-Rayet star of initial mass 25–60 $M_\odot$ (e.g. Brecher & Wasserman 1980, Fesen & Becker 1991). Its low luminosity supports this hypothesis, since there is no historical record of any bright event around 1680, when Flamsteed observed it as a 6th-magnitude star only (Ashworth 1980). Models of Type-Ib supernovae (Hashimoto, Nomoto & Shigeyama 1989, Woosley, Langer & Weaver 1996) predict that they typically produce $5\,10^{-5}$ to $10^{-4}\,M_\odot$ of ^{44}Ti.

Cas A was first seen by COMPTEL with a 1.157 MeV line flux of $(7.0 \pm 1.7)\,10^{-5}\,\gamma\,cm^{-2}\,s^{-1}$ (Iyudin et al. 1994). In the most favourable case (event date 1680, $D = 2.8$ kpc, $\tau = 96.1$ yr), this converts into a ^{44}Ti yield of $1.9\,10^{-4}\,M_\odot$ which implies that substantial amounts of ^{56}Ni powering the light curve were ejected by the supernova. As stressed by Hoffman et al. (1995), this result is difficult to reconcile with ^{44}Ti nucleosynthesis predictions and observational evidence that Cas A was not a bright supernova.

Using COMPTEL data spanning three years, we detect Cas A in the 1.07–1.25 MeV band at the $3.5\,\sigma$ significance level with $-2\ln\lambda = 12.1$. Continuum emission is negligible towards the supernova: measurements in the neighbouring energy bands are below the 1 σ noise level. Emission in the 1.07–1.25 MeV band is then attributable to ^{44}Ti decay.

We derive an updated 1.157 MeV line flux for Cas A of $F_{1.157} = (3.4\pm0.9)\,10^{-5}\,\gamma\,\mathrm{cm^{-2}\,s^{-1}}$, which is in agreement with the latest OSSE findings, $(1.7\pm1.4)\,10^{-5}\,\gamma\,\mathrm{cm^{-2}\,s^{-1}}$ (The et al. 1996). This value is obtained using background model (ii) (Sect. 2.2). In order to assess systematic effects, we have also performed a study of Cas A with method (i) and found $F = (4.0\pm0.9)\,10^{-5}\,\gamma\,\mathrm{cm^{-2}\,s^{-1}}$. The difference between the two values is within 1 σ statistical fluctuations as well as the estimated $\sim$ 25% systematic uncertainty inherent to the analysis.

Depending on the ^{44}Ti lifetime, between 75 and 95 yr, and the SNR distance, $D = 2.8$–3.4 kpc (Reed et al. 1995), the supernova ejected 0.9 to 2.4 10^{-4} $M_\odot$ of ^{44}Ti assuming a 1.157 MeV flux of $3.4\,10^{-5}\,\gamma\,\mathrm{cm^{-2}\,s^{-1}}$. This yield is lower than the earlier values and seems to match our theoretical picture of Cas A. Yet it implies that the supernova was intrinsically bright (Timmes et al. 1996). That the event was hardly attested requires a larger visual extinction than the $A_V \sim 5$ mag measured toward Cas A (Peimbert & van den Bergh 1971), presumably due to the dust and gas shell which surrounded the Wolf-Rayet star at the time of its explosion (Hartmann et al. 1996).

5. The search for sources of ^{44}Ti line emission

Various estimations (Tammann, Löffler & Schröder 1994, van den Bergh & McClure 1994) suggest a supernova rate $\nu_{SN} \sim 2.5$–3.0 events per century in the Milky Way. About 7–9 supernovae are expected to have exploded since Cas A around 1680. However no such event has been attested and no candidate supernova remnant is known.

If supernovae are distributed like Ia : Ib : II $\sim$ 1 : 1.5 : 7.5 (van den Bergh & Tammann 1991), most of them are core-collapse events possibly embedded in the dense clouds that gave birth to their massive progenitors. Column densities $N_H \gtrsim 10^{22}\,\mathrm{cm^{-2}}$ are common within molecular clouds and along the line of sight through the Molecular Ring of the inner Galaxy. With $A_V/N_H \sim 5.3\,10^{-22}\,\mathrm{mag\,cm^2}$ (Bohlin, Savage & Drake 1978), the combined *foreground*, *local*, and even *circumstellar* (Sect. 4.3) obscuration may well exceed 10–15 mag. Beside distance effects, large visual extinction can easily hide supernovae to the observer's eye.

The Milky Way is transparent to gamma rays. Though invisible at optical wavelengths, young SNR s could be betrayed through ^{44}Ti line decay. As exemplified by Cas A, COMPTEL has the potential for detecting these sources. We examine any excess left in the likelihood map of Fig. 2. As explained in Sect. 2.3, we adopt $-2\ln\lambda > 16.5$ ($> 3.3\,\sigma$ significance level) as our criterion for serendipitous source detection. By far, no excess in the map actually fulfils this requirement. We conclude that, *with the sole exception of Cas A, no Galactic source of ^{44}Ti line emission is detected by COMPTEL.*

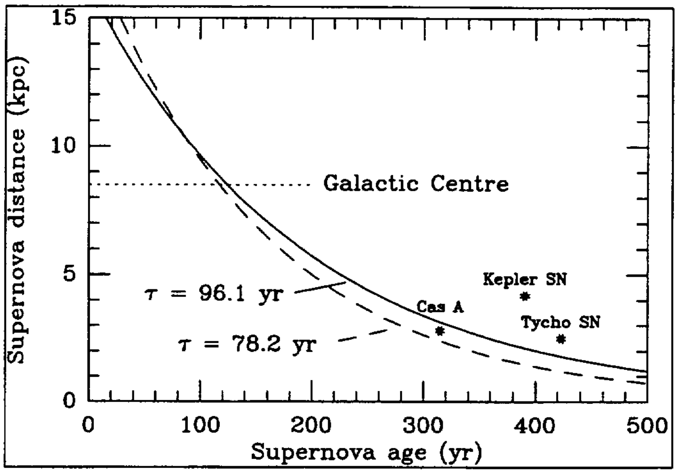

Fig. 3. Age-distance detectability of a supernova through ^{44}Ti decay. The curves correspond to a present-day 1.157 MeV line flux $F_{1.157} = 2\,10^{-5}\,\gamma\,\mathrm{cm^{-2}\,s^{-1}}$ for a mean lifetime $\tau = 96.1$ yr (*solid line*) or 78.2 yr (*dashed line*). A yield $Y_{44} = 7\,10^{-5}\,M_\odot$ is assumed. If this flux level is adopted as the detection threshold, COMPTEL has access to SNR s located in the lower left region delimited by these curves. Note that $D \propto (Y_{44}/F_{1.157})^{1/2}$ for a given age t. Zero-age supernovae are detectable by COMPTEL up to 15–20 kpc, a range excluding SN 1987A in the LMC.

With $-2\ln\lambda = 13.4$, the excess located at $l = 157.5°$ and $b = -23.5°$ is worth a mention. Although far off the Galactic plane, it is associated with a star-formation complex in Perseus which includes the molecular cloud IC 348 (Ungerechts & Thaddeus 1987) as well as a young cluster of intermediate-mass stars at the edge of the Perseus OB 2 association (Herbig & Jones 1983). Assuming a distance of $D \sim 350$ pc (Ungerechts & Thaddeus 1987) and a fiducial ^{44}Ti yield $Y_{44} = 0.7\,10^{-4}\,M_\odot$, the COMPTEL 1.157 MeV line flux of $(3.9\pm1.1)\,10^{-5}\,\gamma\,\mathrm{cm^{-2}\,s^{-1}}$ might be interpreted as a hint for a supernova event in Perseus some 700 years ago. More data are obviously required before any definite statement can be made about this excess.

Whether COMPTEL is expected to detect a supernova depends on the distance D and age t of the event [Eq. (2)]. Let us take a flux threshold $F_{1.157} = 2\,10^{-5}\,\gamma\,\mathrm{cm^{-2}\,s^{-1}}$ as the instrument sensitivity (Sect. 4.1). Assuming an initial ^{44}Ti mass of $Y_{44} = 0.7\,10^{-4}\,M_\odot$, we build the age-distance diagram of Fig. 3. Events of the past hundred years appear detectable by COMPTEL up to $D = 10$ kpc. This includes the Galactic Centre and represents about half of the Milky Way. For 19th-century events, the accessible domain still encompasses the forefront part of the molecular ring. With $\nu_{SN} \sim 2.5$–3.0 per century, we then expect COMPTEL to detect about 3 SNR s from the last 200 years.

From the HEAO 3 and SMM measurements, important constraints have been put on the Galactic rate (ν_{SN}) and nucleosynthesis models (Y_{44}) of supernovae (Hartmann et al. 1993, Leising & Share 1994). Our negative 1.157 MeV survey strengthens these constraints. None of the 3 sources expected on statistical grounds is clearly seen by COMPTEL. If supernova occurence follows Poisson's statistics, *this is consistent at the less than 5% confidence level* with the canonical rate $\nu_{SN} \sim 2.5$ Galactic events per century and typical yield $Y_{44} = 0.7\,10^{-4}\,M_\odot$.

As emphasised by Leising (1994), this stringent result is puzzling since the Galactic abundance of ^{44}Ca imposes a contradictory conclusion. Simple arguments (Leising & Share 1994) lead to the expectation that about $4\,10^{-4}\,M_\odot$ of ^{44}Ca are produced per average century. This value must be equal to $Y_{44} \times \nu_{SN}$ if ^{44}Ti is the only natural parent of ^{44}Ca. Do detonating helium white dwarfs, very rare SN Ip events which release as much as $10^{-2}\,M_\odot$ of ^{44}Ti (Woosley, Taam & Weaver 1986), synthesise most Galactic ^{44}Ca? Or has this side of the Milky Way been excessively supernova-quiet over more than two centuries?

So far, Cassiopeia A is the only ^{44}Ti source detected by COMPTEL. It should probably be left to X-ray (XTE and SAX) or future gamma-ray (INTEGRAL) missions to unveil other supernova remnants either older (SN 1572, SN 1604) or located farther away in the Galaxy. Yet more discoveries may await COMPTEL at 1.157 MeV, triggered by further observations of sky regions where the current exposure is still poor. The Perseus excess seems the most promising target for further study.

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