Gamma-Ray Observations of Explosive Nucleosynthesis Products
Jacco Vink \textsuperscript{a}

\textsuperscript{a} SRON National Institute for Space Research, Sorbonnelaan 2, 3584 CA Utrecht, The Netherlands

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Abstract

In this review I discuss the various \( \gamma \)-ray emission lines that can be expected and, in some cases have been observed, from radioactive explosive nucleosynthesis products. The most important \( \gamma \)-ray lines result from the decay chains of \( ^{56}\text{Ni} \), \( ^{57}\text{Ni} \), and \( ^{44}\text{Ti} \). \( ^{56}\text{Ni} \) is the prime explosive nucleosynthesis product of Type Ia supernovae, and its decay determines to a large extent the Type Ia light curves. \( ^{56}\text{Ni} \) is also a product of core-collapse supernovae, and in fact, \( \gamma \)-ray line emission from its daughter product, \( ^{56}\text{Co} \), has been detected from SN1987A by several instruments. The early occurrence of this emission was surprising and indicates that some fraction of \( ^{56}\text{Ni} \), which is synthesized in the innermost supernova layers, must have mixed with the outermost supernova ejecta.

Special attention is given to the \( \gamma \)-ray line emission of the decay chain of \( ^{44}\text{Ti} \) (\( ^{44}\text{Ti} \rightarrow ^{44}\text{Sc} \rightarrow ^{44}\text{Ca} \)), which is accompanied by line emission at 68 keV, 78 keV, and 1157 keV. As the decay time of \( ^{44}\text{Ti} \) is \( \sim 86 \) yr, one expects this line emission from young supernova remnants. Although the \( ^{44}\text{Ti} \) yield (typically \( 10^{-5} - 10^{-4} \, M_\odot \)) is not very high, its production is very sensitive to the energetics and asymmetries of the supernova explosion, and to the mass cut, which defines the mass of the stellar remnant. This makes \( ^{44}\text{Ti} \) an ideal tool to study the inner layers of the supernova explosion. This is of particular interest in light of observational evidence for asymmetric supernova explosions.

The \( \gamma \)-ray line emission from \( ^{44}\text{Ti} \) has so far only been detected from the supernova remnant Cas A. I discuss these detections, which were made by \textit{COMPTEL} (the 1157 keV line) and \textit{BeppoSAX} (the 68 keV and 78 keV lines), which, combined, give a flux of \( (2.6 \pm 0.4 \pm 0.5) \times 10^{-5} \) ph cm\(^{-2}\) s\(^{-1}\) per line, suggesting a \( ^{44}\text{Ti} \) yield of \( (1.5 \pm 1.0) \times 10^{-4} \, M_\odot \). Moreover, I present some preliminary results of Cas A observations by \textit{INTEGRAL}, which so far has yielded a 3\( \sigma \) detection of the 68 keV line with the ISGRI instrument with a flux that is consistent with the \textit{BeppoSAX} detections. Future observations by \textit{INTEGRAL}-ISGRI will be able to constrain the continuum flux above 90 keV, as the uncertainty about the continuum shape, is the main source of systematic error for the 68 keV and 78 keV line flux measurements. Moreover, with the \textit{INTEGRAL}-SPI instrument it will be possible to measure or constrain the line broadening of the 1157 keV line. A preliminary analysis of the available data indicates that narrow line emission (i.e. \( \Delta v < 1000 \) km s\(^{-1}\)) can be almost excluded at the 2\( \sigma \) level, for an assumed line flux of \( 1.9 \times 10^{-5} \) ph cm\(^{-2}\) s\(^{-1}\).

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1. Introduction

Nature’s heaviest elements are the products of explosive nucleosynthesis in supernovae. A large fraction of the explosive nucleosynthesis products begin as radioactive elements. This is in particular the case for Type Ia supernovae, which, according to the standard scenario, are the result of thermo-nuclear disruptions of carbon-oxygen white dwarfs with a mass close to the Chandrasekhar limit. The energy for the disruption comes from the thermo-nuclear burning of C and O into \( \sim 0.6 \, M_\odot \) of \( ^{56}\text{Ni} \), a radioactive element that is the source of \( ^{56}\text{Fe} \), the most abundant iron isotope (see e.g. \cite{Arnett1996}).

For core-collapse supernovae, explosive nucleosynthesis is not the driver behind the explosion (the energy comes from the gravitational collapse of the stellar core). The hot, inner regions of the supernova typically produce 0.1 \( M_\odot \) of \( ^{56}\text{Ni} \), but with a larger variation in yield from one core collapse event to another.

The most telltale signs of the synthesis of radioactive material are the lengths and shapes of supernova light curves. Although the expanding plasma cools adiabatically, radioactivity heats the plasma making the supernova visible for an extended period. The amount of radioactive material can be estimated from modeling the light curves, taking into account radiative transfer in the expanding atmosphere, which \( \gamma \)-rays emerge is an important diagnostic tool in it- self. The \( \gamma \)-ray emission from the radioactive elements can in principle be observed directly. Although in the early phases of the supernova the atmosphere is opaque to \( \gamma \)-rays, at later phases \( \gamma \)-ray emission should emerge. In fact the phase at which \( \gamma \)-rays emerge is an important diagnostic tool in itself \cite{Hofflich1995}. The spectral information can be used to measure the velocity distribution of the radioactive material. The goal of \( \gamma \)-ray observations of fresh radioactive material is to provide new insights into the yields, expansion velocities and asymmetries of the explosive nucleosynthesis products. Moreover, the line emission from the longer lived
radioactive element $^{44}$Ti is a tracer of recent supernova activity.

For Type Ia supernovae $\gamma$-ray observation can be used to distinguish between various explosion models, such as “delayed detonation” and He-detonation of sub-Chandrasekhar mass white dwarfs (Woosley and Weaver, 1994). This is of particular interest for cosmology, as Type Ia supernovae are used as standard candles (e.g. Riess et al., 2004), but the variation in absolute peak brightness and its correlation with light curve properties (Phillips, 1993), which is used to calibrate the absolute brightness of the supernovae, is not well understood. The brightness variation is likely to reflect a variation in $^{56}$Ni yield, but the cause of this variation is still under debate (e.g. Mazzali et al., 2001; Röpke et al., 2004).

For core-collapse supernovae the prime interest is to understand the nature of the explosion mechanism. This has become more important now that gamma-ray bursts appear to be related to core-collapse supernovae, which challenges our view of the core-collapse explosion mechanism in general. There are two main hypotheses about the likely bipolar nature of gamma-ray bursts, the collapsar model (MacFadyen et al., 2001), or, alternatively, jet-formation due to magneto-rotational instabilities (Akiyama et al., 2003b).

In particular the latter hypothesis may, to some extent, be relevant for all collapse explosions. A case in point is the discovery of a jet-counter jet system in the supernova remnant Cas A (Fig. 1; Vink, 2004; Hwang et al., 2004; Hines et al., 2004), and the non-spherical expansion of its bright Si-rich shell (Markert et al., 1983; Willingale et al., 2002). On the other hand, recent simulations of more conventional core-collapse supernovae indicate a highly turbulent nature of the inner regions, which may give rise to $^{56}$Ni-rich high-velocity material. This high velocity material may finally be ejected with a high velocity, if the star has a low envelope mass, e.g. due to stellar wind mass losses, as is thought to be the case for Type Ib/c supernovae (Kifonidis et al., 2003). This may be the cause of the Fe-rich “bullets” in Cas A that have overtaken the Si-rich shell of ejecta (Hwang and Laming, 2003). Cas A, a likely Type Ib remnant, will feature prominently here, as it is the only confirmed source of $^{44}$Ti $\gamma$-ray emission, and an important target of the INTEGRAL $\gamma$-ray mission.

2. Gamma-ray lines from supernovae

Table 1 list the most important radioactive elements produced by explosive nucleosynthesis (for more general reviews on $\gamma$-ray line emission, see Diehl and Timmes, 1998; Prantzos, 2004). In the case of electron capture, additional lines in the X-ray band will arise from characteristic de-excitations of the atomic shells of a few key isotopes (Leising, 2001).

1Another long lived element that traces recent stellar nucleosynthesis is $^{26}$Al at 1809 keV, with a decay time of $1.1 \times 10^6$ yr. However, the most likely dominant source of $^{26}$Al is not supernovae, but the winds of massive stars (Prantzos, 2004).

The most abundant radioactive nucleosynthesis product, $^{56}$Ni, is the product of Si-burning and $\alpha$-rich freeze-out, whereas $^{44}$Ti is almost exclusively the product of $\alpha$-rich freeze-out in core-collapse supernovae (Arnett, 1996; The et al., 1998), although sub-Chandrasekhar mass Type Ia supernovae may be an additional source of $^{44}$Ti (Woosley and Weaver, 1994). Alpha-rich freeze-out occurs when material that is initially in nuclear statistical equilibrium cools adiabatically in the presence of an $\alpha$ particle excess caused by the triple-alpha reaction bottleneck. This makes the $^{44}$Ti yield very sensitive to the explosion energy and asymmetries, as faster expansion causes a more rapid freeze out. The yield is also very sensitive to the place of the mass cut, as $^{44}$Ti is synthesized in the deepest supernova layers, close to the mass cut.

Finally, $\gamma$-rays observed from the inner Galaxy from electron-positron annihilation, consisting of 511 keV line emission, and three photon continuum decay of positronium, may also find its origin in explosive nucleosynthesis. The reason is that the $\beta$-decays of $^{56}$Co and $^{44}$Sc produce positrons. Due to its long lifetime almost all positrons from $^{44}$Sc will escape the supernova, but this is less clear for $^{56}$Co, as its decay takes place during the earlier phases of the supernova, when the density is high (Colgate, 1970; Chan and Lingenfelter, 1993; Milne et al., 1999). However, more $^{56}$Co positrons will escape if the expansion is fast (Cassé et al., 2004; Vink, 2004). This led Cassé et al. (2004) to the suggestion that a hypernova in the Galactic center region may be responsible for the 511 keV electron-positron line emission from that region (Kinzer et al., 2001).

2The mass cut defines the boundary of material that will be ejected, versus what will fall back on the stellar remnant (neutron star or black hole).
Table 1
Decay chains and γ-ray signatures of shortlived radioactive products from explosive SN nucleosynthesis.

| Decay time | Process | Lines (keV) |
|------------|---------|-------------|
| 56Ni → 56Co | 56Fe | 8.8 d EC | 158, 812 |
| 57Ni → 57Co | 57Fe | 111.3 d EC, $e^+$ (19%) | 847, 1238 |
| 44Ti → | 44Sc | 44Ca | 52 hr EC | 122 |
| | | | 390 d EC | 122 |
| | | | 86.0 yr EC | 122 |
| | | | 5.7 hr $e^+$, EC (1%) | 1157 |

Table 1 continued...

Knödlseder et al. [2003] Knödlseder et al. [2005, in preparation]

2.1. Detections of $^{56}$Co lines from SN 1987A.

The importance of future γ-ray observations of supernovae can be easily justified by the impact of the detection of γ-ray lines from SN 1987A. The 847 keV and 1238 keV $^{56}$Co lines were detected by a number of balloon experiments (Cook et al., 1988; Mahoney et al., 1988; Sandie et al., 1988; Teegarden et al., 1989), and the gamma-ray spectrometer (GRS) on board the Solar Maximum Mission (SMM) satellite (Matz et al., 1988; Leising and Share, 1990) see Fig. 2. The observed fluxes were typically in the range $(0.5 - 1) \times 10^{-3}$ ph cm$^{-2}$s$^{-1}$, indicating that only a few percent of the total $\sim 0.075 M_\odot$ of $^{56}$Co was exposed. The detection of 122 keV line emission from $^{57}$Co by the Oriented Scintillation Spectrometer Experiment (OSSE) on board the Compton Gamma Ray Observatory (CGRO) was later reported by Kurfess et al. (1992).

Although the emergence of $^{56}$Co γ-ray lines had been predicted (Clayton and Silk, 1969), it was a surprise that the lines became observable as early as 160 days after the explosion (Matz et al., 1988). $^{56}$Co was expected to be buried too deep into the ejecta to be observable, but the early detection indicates that at least some of the $^{56}$Co must have mixed out to larger radii. In velocity coordinates this means that $\sim 5\%$ of iron-group rich material must have mixed out to velocities of $\sim 3000$ km s$^{-1}$ (Arnett et al., 1989; Leising and Share, 1990, and reference therein), while most of the iron-group material is thought to have a velocity less than 1000 km s$^{-1}$. The cause for this mixing may be Rayleigh-Taylor instabilities, and, in addition, the expansion of $^{56}$Ni/56Co-rich bubbles caused by radioactive heating (e.g. Basko, 1994; Kifonidis et al., 2003).

Models for γ-ray emission that include ejecta mixing predict that the γ-ray lines should be blue-shifted, as only the γ-rays from the expanding sphere facing us should be observable (Pinto and Woosley, 1988). However, the high spectral resolution observations of SN 1987A showed that the 847 keV and 1238 keV lines were broadened by $\sim 3000$ km s$^{-1}$ (FWHM) and redshifted by $\sim 400$ km s$^{-1}$ (Sandie et al., 1988; Teegarden et al., 1989; Teueller et al., 1990). This discrepancy is still not understood, but it clearly points to an asymmetric explosion. The γ-ray emission from SN 1987A thus adds another piece to the puzzle of understanding the nature of core-collapse supernovae.

2.2. Gamma-ray observations of Type Ia supernovae

As explained above, nucleosynthesis in Type Ia supernovae, is the cause for the explosion, and not merely a byproduct of the explosion, as for core collapse supernovae. Gamma-ray observations of Type Ia therefore promise to give new insights into the light curve variation among Type Ia supernovae. Unfortunately, no solid detections of $^{56}$Ni and $^{56}$Co line emission have been made, as there has been a lack of sufficiently nearby Type Ia events. The best candidate for γ-ray observations was SN 1991T, a relatively bright Type I supernova (Phillips, 1993) at a distance of $\sim 13.5$ Mpc.

Both OSSE and the Compton Telescope (COMPTEL) on board CGRO observed this supernova remnant. An initial analysis of the COMPTEL data and the OSSE data resulted in upper limits on $^{56}$Co lines fluxes of $3 - 4 \times 10^{-5}$ ph cm$^{-2}$s$^{-1}$ (resp. Lichti et al., 1994; Leising et al., 1995). However, a
reanalysis of the COMPTEL observation showed evidence for line emission at the $\sim 3\sigma$ level (Morris et al., 1997). Although it is uncertain whether the COMPTEL detection holds up, the predicted $^{56}$Co line fluxes for SN 1991T were close to the COMPTEL and OSSE upper limits. This gives some hope that INTEGRAL will be able to detect a not too distant Type Ia supernova in the near future.

### 2.3. $^{44}$Ti detections by COMPTEL & BeppoSAX

One of the highlights of the COMPTEL experiment is the detection of the 1157 keV line associated with the decay of $^{44}$Ti (Iyudin et al., 1994). Cas A is the youngest known Galactic supernova remnant, and is probably the result of a Type Ib or Ic supernova (Vink, 2004, for a review). So of all remnants Cas A was the most likely source of $^{44}$Ti. On the other hand, Cas A exploded around 1672 and given the expected $^{44}$Ti yields of around $10^{-5} M_\odot$ (e.g. Woosley and Weaver, 1995), the 1157 keV line flux should have been below the COMPTEL detection limit. Surprisingly, COMPTEL detected the 1157 keV line emission, with the latest, most reliable flux estimate based on COMPTEL observations being $(3.4 \pm 0.9) \times 10^{-5}$ ph cm$^{-2}$ s$^{-1}$ (Schönenfelder et al., 2000).

The $^{44}$Ti decay chain also produces line emission at 67.9 keV and 78.4 keV. Several observation with OSSE, RXTE-HEXTE, and BeppoSAX-PDS were made in order to confirm the high $^{44}$Ti flux, but without success (The et al., 1996; Rothschild et al., 1999; Vink et al., 2000). The most stringent flux upper limit ($< 4 \times 10^{-5}$ ph cm$^{-2}$ s$^{-1}$), obtained with the BeppoSAX-PDS, was in fact below the original COMPTEL flux measurement (Vink et al., 2000).

This discrepancy was finally solved with a 500 ks observation of Cas A by BeppoSAX which resulted in the first detection of the 67.9 keV and 78.4 keV lines (Vink et al., 2001, see Fig. 3). A complication for measuring the line fluxes of the low energy lines is the presence of continuum emission from Cas A. The nature of the continuum emission is unknown, and interesting in its own right. It could be either due to synchrotron radiation from electrons with energies in the TeV range (Allen et al., 1997; Reynolds, 1998), or it could arise from bremsstrahlung by supra-thermal electrons, which have been accelerated by internal shocks (Laming, 2001b), or by Fermi acceleration at the forward shock (Asvarov et al., 1999). Both the synchrotron and the non-thermal bremsstrahlung model by Laming predict a gradual steepening at high energies. Unfortunately there are no reliable continuum flux measurements at energies just above the 78.4 keV line. As a result, assuming that the continuum is a simple power-law spectrum gives a line flux for each line of $(1.9 \pm 0.4) \times 10^{-5}$ ph cm$^{-2}$ s$^{-1}$ (68% confidence range), whereas the gradual steepening of synchrotron and specific non-thermal bremsstrahlung models results in a line flux of $(3.2 \pm 0.3) \times 10^{-5}$ ph cm$^{-2}$ s$^{-1}$ (Vink et al., 2001; Vink and Laming, 2003). Within the errors both values are consistent with the latest COMPTEL results (Schönenfelder et al., 2000). We can average the COMPTEL and BeppoSAX results to obtain a $^{44}$Ti line flux of $(2.6 \pm 0.4 \pm 0.5) \times 10^{-5}$ ph cm$^{-2}$ s$^{-1}$ per line, where the first error is the $1\sigma$ statistical error and the second error is the systematic error, due to uncertainty in the continuum modeling.

### 2.4. The $^{44}$Ti yield of Cas A

The detection of $^{44}$Ti in Cas A led to a renewed interest in measuring the life time of $^{44}$Ti, which was highly uncertain, with published life times varying between 67 yr and 96 yr (Diehl and Timmes, 1998). In 1998, however, accurate measurements by three independent groups give a life time of 85 yr (Ahmad et al., 1998; Görres et al., 1998; Norman et al., 1998). Meanwhile more measurements have been published in agreement with these results (Wietfeldt et al., 1999; Hashimoto et al., 2001). The error weighted average of these results gives a life time of $86.0 \pm 0.5$ yr.

The distance to Cas A is $3.4^{+0.3}_{-0.1}$ kpc (Reed et al., 1995), and the most recent estimate of the supernova event is A.D. 1671.3 $\pm$ 0.9 (Thorstensen et al., 2001). The $\gamma$-ray emission implies an initial $^{44}$Ti mass of $M_0(^{44}$Ti$) = (1.6 \pm 0.3$ $\pm 8$ Note that Vink et al. (2003) list 90% errors, whereas for weighing the results and assessing the total statistical error $1\sigma$ (68%) errors are used (c.f. Vink and Laming, 2003).

4This is close to the putative data of A.D. 1680 of the detection of a putative supernova by Flamsteed (Ashworth, 1980), but the connection of Flamsteed’s observation with the supernova is debatable, rejected by Stephenson and Green (2002).
SN 1987A, which, based on the light curve, is estimated to be a star that exploded with a final mass of 4. The standard models are shown as crosses (based on Woosley and Weaver (1995) for which the explosion energy was increased (1 foe = 10^{51} erg) and triangles (Nomoto et al., 1997) under lower than for Cas A, as pointed out by Mochizuki et al. (1999); Motizuki and Kumagai (2004). The reason is that 44Ti decays through electron capture, which in most cases involves the capture of one of the inner most, K-shell, electrons. If the 44Ti is sufficiently ionized, i.e. one or both K-shell electrons are absent, the electron capture rate drops significantly. However, to have an effect the ionization should be already present in the He-like state (e.g. Vink et al., 1996). This means that the K-shell is fully populated, and only a modest effect of ~10% on the life time is to be expected. Moreover, a substantial fraction of 44Ti may not yet have been heated by the reverse shock. Finding this out is one of the goals of INTEGRAL observations of Cas A. More detailed hydrodynamical calculations also indicate that the ionization history has only a minor effect on the 44Ti line flux (Laming, 2001c).

2.5. Implications of the 44Ti yield

A comparison of the 44Ti yield of Cas A with model calculations (Fig. 4) shows that nucleosynthesis models predict the observed yield. Taken at face value this implies that the supernova event must have been a more energetic event (e.g. 2 × 10^{51} erg instead of the canonical 10^{51} erg), an asymmetric supernova (Nagataki et al., 1998), or the result of the explosion of a star that lost most of its mass (Woosley et al., 1995). As for the effects of asymmetry, Maeda and Nomoto (2003) consider various bipolar supernova models, which indeed give a higher 44Ti yield. However, the higher 44Ti yields of their models seem to be largely caused by the high kinetic energy, ~ 10^{52} erg, of the explosion models rather than due to the bipolar nature of the explosions, as a comparison of the bipolar and spherical models (resp. models 40A and 40SHA) shows. On the other hand, the bipolar models have a higher 44Ti/56Ni ratio, which is in better agreement with the 44Ti and 56Ni estimates of SN 1987A.

Both mass loss and a higher explosion energy result in a reduced fall back of ejecta on the proto-neutron star/black hole, since both affect the final velocity of the ejecta. It can be argued that for Cas A all those effects play a role. After all, Cas A was probably a Type Ib supernova, and the ejecta mass as measured in X-rays is quite low, in the range 2-4M⊙. Furthermore, the kinetic energy, as derived from the supernova remnant’s kinematics (Vink et al., 1998; DeLaney et al., 2002) has been estimated to be ~ 2 × 10^{51} erg (Laming and Hwang, 2003). Finally, there is ample evidence for asymmetric ejecta expansion (Hwang and Laming, 2003; Vink, 2004; Hwang et al., 2004).

The 44Ti yield, therefore, strengthens our current ideas about Cas A, but one should keep in mind that the predicted 44Ti yields are uncertain. Most simulations are based on one-dimensional models, in which artificially energy or momentum is deposited at the base of the ejecta. Multidimensional models of core-collapse supernovae show that the ejecta kinematics is highly turbulent, which is likely to have an effect on the 44Ti yield. Moreover, there is still uncertainty whether magnetic fields and rotation are important for the explosion mechanism (Akivama et al., 2003b).

It is worthwhile to note that the high fluxes associated with 44Ti decay from Cas A, might also be the result of a change in effective life-time of 44Ti, as pointed out by Mochizuki et al. (1999); Motizuki and Kumagai (2004). The reason is that 44Ti decays through electron capture, which in most cases involves the capture of one of the inner most, K-shell, electrons. If the 44Ti is sufficiently ionized, i.e. one or both K-shell electrons are absent, the electron capture rate drops significantly. However, to have an effect the ionization should have taken place early in the life of the remnant, in order to inhibit the decay of a substantial amount of 44Ti. This is unlikely to be the case for Cas A, given the fact that X-ray spectroscopy indicates that both Ca and Fe, which have similar ionization cross sections, are still ionizing\(^3\) and are presently in the He-like state (e.g. Vink et al., 1998a). This means that the K-shell is fully populated, and only a modest effect of ~10% on the life time is to be expected. Moreover, a substantial fraction of 44Ti may not yet have been heated by the reverse shock. Finding this out is one of the goals of INTEGRAL observations of Cas A. More detailed hydrodynamical calculations also indicate that the ionization history has only a minor effect on the 44Ti line flux (Laming, 2001c).

2.6. Potential other sources of 44Ti γ-ray emission

The Galactic supernova rate is thought to be approximately 2 per century. However, the latest observed supernova was observed in A.D. 1604 (Kepler’s supernova Stephenson and Greed, 2002), and the youngest remnant known, Cas A, was also a 17th century event. It is unlikely\(^6\) that these two supernovae were truly the last, so other supernovae must have been too dim to be noted, and their remnant.

\(^3\)Even when instantly heated it takes some time before an atom is ionized up to equilibrium ionization. This is governed by the product of electron density and time, n_e \cdot t. A hot plasma is roughly in equilibrium ionization if n_e \cdot t \sim 10^{12} \text{ cm}^{-3}\text{s}, whereas in Cas A it is typically n_e \cdot t \sim 10^{11} \text{ cm}^{-3}\text{s}.

\(^6\)The chance that no supernova occurred in the Galaxy since 1672, given a rate of 2 per century, is 0.17%.
nants may still escape our attention. The reason could be that Galactic supernovae have been heavily obscured, and their remnants are faint because they evolve in low density regions.

The $\gamma$-ray emission from $^{44}$Ti, however, does not depend on the environment of the supernova, and $\gamma$-rays can uninhibitedly penetrate the interstellar medium. Gamma-ray observations of $^{44}$Ti line emission is therefore a possible method for discovering young remnants.

A search for $^{44}$Ti in the Galactic plane was made with COMPTEL, initially without finding any obvious candidate sources (Dupraz et al. 1997; Iyudin et al. 1999), but later a potential $^{44}$Ti source, GRO J0852-46.2, was discovered close to the Vela supernova remnant (Iyudin et al. 1998). The Vela supernova remnant is too old to contain a significant amount of $^{44}$Ti, but ROSAT observations of the Vela region showed the presence of a supernova remnant, RX J0852.0-4622/G266.2-1.2, in projection to the Vela supernova remnant (Aschenbach 1998), which is often affectionately referred to as “Vela Jr”.

Although, the COMPTEL observation triggered the discovery of the new remnant, it is not clear whether it is truly a source of $^{44}$Ti. First of all, the X-ray absorption is relatively high (Slane et al. 2001), indicating a distance beyond the Vela (“Sr”) remnant, but it is also rather extended, 2”. Together this suggests a remnant with an age of more than 1000 yr, which is hard to reconcile with the observed 1157 keV line flux of $(3.8 \pm 0.7) \times 10^{-9} \text{ph cm}^{-2} \text{s}^{-1}$ (Aschenbach et al. 1999; Slane et al. 2001). Also the detection itself, although formally at the 5$\sigma$ level is less secure than the detection of $^{44}$Ti in Cas A (Schönfelder et al. 2000). Nevertheless, Vela Jr is an interesting object and an important INTEGRAL target (von Kienlin et al. 2004).

3. INTEGRAL

The International Gamma-Ray Astrophysics Laboratory (INTEGRAL) is ESA’s $\gamma$-ray imaging and spectroscopy mission and was launched in October 2002 (Winkler et al. 2003). The two main $\gamma$-ray instruments are the spectrometer SPI (Vedrenne et al. 2003) and the imager IBIS (Ubertini et al. 2003), both of which use coded masks to obtain positional information.

IBIS has a fully coded field of view of 5” $\times$ 5”, and an angular resolution of 3’. Its principal detector plane instrument is ISGRI (Lebrun et al. 2003), consisting of 128 $\times$ 128 CdTe detectors. SPI, on the other hand, uses 19 Ge detectors, giving a limited spatial resolution of 2.5” (FWHM), but a spectral resolution of $\Delta E = 3$ keV over a wide energy range from 20 keV - 8 MeV. This results in a very high line resolving power, in particular for MeV energies.

SPI is the main instrument for $\gamma$-ray-line emission, and has already obtained results on the 1809 keV $^{20}$Al line emission from the Galactic plane (Diel et al. 2004), and the 511 keV annihilation line from the Galactic Center (Jean et al. 2003; Knödlseder et al. 2003). Moreover, a comprehensive study of the available data puts new constraints on the 511 keV emission from the Galactic plane (Reege et al. 2004).

One of the main mission goals of INTEGRAL is to detect and measure $^{44}$Ti emission from young known, or still to be discovered, supernova remnants. There are several projects to observe $^{44}$Ti line emission. The pointed observations concern the (potential) $^{44}$Ti sources “Vela Jr” (section 3), SN 1987A, Tycho and Cas A. For preliminary INTEGRAL results on “Vela Jr” and supernova remnants searches in the $^{44}$Ti lines, see (von Kienlin et al. 2004) and (Renaud et al. 2004).

3.1. Cas A

As a known $^{44}$Ti source Cas A is an important INTEGRAL target. The main goal of observing Cas A with INTEGRAL is to obtain an independent measurement of the 67.9 keV, 78.4 keV and 1157 keV line fluxes, and, moreover, to measure, or put strong limits, on the $^{44}$Ti kinematics. The kinematics is of particular interest, given the evidence that the explosion of Cas A was asymmetric, and some fraction of the Fe-rich ejecta must have been ejected with a velocities of 4500-7800 km s$^{-1}$ (e.g. Vink 2004). This Fe is likely to be the decay product of $^{56}$Ni, which was, like $^{44}$Ti, synthesized in the hottest regions, deep inside the supernova. However, only the shocked Fe can be observed in X-rays, so it is possible that most Fe, and therefore most $^{44}$Ti, moves with velocities below 1000 km s$^{-1}$ and has not yet been heated by the reverse shock. Note that the $\gamma$-ray line emission of $^{44}$Ti, unlike X-ray line emission, does not depend on the local conditions (except if the $^{44}$Ti has been almost completely ionized, see section 2.3).

Measuring the $^{44}$Ti velocity may therefore cast new light on the explosion mechanism of core-collapse supernovae. Unfortunately, the line sensitivity of SPI decreases substantially as a function of line broadening. For example, for a narrow line one can obtain a 3$\sigma$ detection of the 1157 keV line with SPI with a 2 Ms exposure, but this is only 1.9$\sigma$ if the lines are broadened with 2000 km s$^{-1}$ FWHM. One can increase the sensitivity, however, by using not only the single detector events, but also events that are registered in two detectors, due to a Compton interaction.

Up to January 2005, INTEGRAL has completed the first two cycles of observations of Cas A, with a total exposure of 3 Ms. The December 2004 observations have not yet been processed at the time of this writing, but the first 1.6 Ms of INTEGRAL observations have resulted in a detection of Cas A by the IBIS-ISGRI instrument. The data were analyzed with the standard INTEGRAL software package OSA.

7Unfortunately, one of the Ge detectors failed in December 2003, and another in July 2004, decreasing the sensitivity of the instrument by 10%.
Figure 5. Left top panel: *INTEGRAL*-ISGRI significance map of the Cas A field for the 20-50 keV band. The brightest source in the field is the high mass X-ray binary 2S 0114+650 (e.g. Hall et al. 2000). Right top panel: *INTEGRAL*-SPI significance map for the 1142-1172 keV band, selecting both single and double events (SE and ME2). The location of Cas A is indicated by a circle with a radius of 2”, the coordinates shown are Galactic. Bottom panel: *INTEGRAL*-ISGRI spectrum of Cas A. The *BeppoSAX*-PDS points are shown in light gray for comparison (Fig. 3).
v3 and, more recently, v4.2. In order to minimize the flux errors due to calibration uncertainties, we estimated fluxes by comparing the Cas A source signal per energy bin directly with that of the Crab nebula. For the conversion to flux units we used the parametrization of the Crab spectrum by Willingale et al. (2001).

The IBIS-ISGRI spectrum is shown in Fig. 5 and is fully consistent with the BeppoSAX-PDS spectrum. There is a clear signature of excess emission with respect to a power-law continuum emission, and the detection significance of the 67.9 keV line is at the 3σ level with a flux of $(2.3 \pm 0.8) \times 10^{-5} \text{ ph cm}^{-2}\text{s}^{-1}$. The 78 keV is not detected, but fitting the 67.9 keV and 78.4 keV jointly, using a power-law continuum, both the measured flux per line $(1.2 \pm 0.6) \times 10^{-5} \text{ ph cm}^{-2}\text{s}^{-1}$, and the power law index, $3.27 \pm 0.15$, are consistent with the BeppoSAX-PDS measurements.

Further results based on the full cycle 1 and 2 data are expected in the near future (Vink et al. 2005, in preparation). In addition, 2.5 Ms of observation time have been approved for cycle 3, which is expected to yield a detection of the continuum above 90 keV, if the continuum has indeed a power law shape. This is important, as the apparent low 78.4 keV line flux may in fact be caused by a steepening of the continuum above ~ 60 keV. This would be of great interest, as a steepening is predicted for all synchrotron and some bremsstrahlung models (section 2.3).

It is clear that INTEGRAL-IBIS has not yet improved upon the BeppoSAX measurement of Cas A. However, this is expected to change in the near future. Moreover, IBIS is an imaging instrument, whereas BeppoSAX-PDS was a narrow field instrument using a collimator (Frontera et al. 1997). As a result IBIS can observe a large field and separate point sources, but the use of coded masks requires a larger detector area, which causes a relatively large background signal. The advantage is that we can now resolve several hard X-ray sources in the field of Cas A, which allows us to exclude the possibility that a hard X-ray source was contaminating the BeppoSAX-PDS spectrum of Cas A. Moreover, with IBIS it is possible to observe simultaneously Cas A and Tycho, and in addition it reveals the presence of many unresolved sources, two of which were not previously known as hard X-ray sources (den Hartog et al. 2004).

Figure 5 shows an IBIS-ISGRI and a SPI significance map. The SPI map is made with the spiro software using the mean count modulation (MCM) method for the background modeling (Skinner and Connell 2003). Both single and double detector events were used, excluding time intervals with high background rates. The map shown in Fig. 5 covers the energy range 1142-1172 keV, which corresponds to a total velocity width of $\pm 7800 \text{ km s}^{-1}$, the velocity width that can be expected if most of the $^{44}\text{Ti}$ is situated in or is interior to the bright X-ray shell (Willingale et al. 2002). Neither this map, nor the analysis of the available data in a narrow energy range from 1155 keV to 1159 keV yield a significant detection. However, a 1.8σ excess is found within $2^\circ$ of the position of Cas A with a flux of $1.8 \times 10^{-5} \text{ ph cm}^{-2}\text{s}^{-1}$, similar to the flux measured by BeppoSAX and INTEGRAL-IBIS.

A preliminary analysis shows that narrow line $^{44}\text{Ti}$ emission ($\Delta E = 4 \text{ keV}, \Delta v = 1000 \text{ km s}^{-1}$) can almost be excluded at the 2-3σ level, as the 3σ upper limit for emission is $3.1 \times 10^{-5} \text{ ph cm}^{-2}\text{s}^{-1}$, the flux level found by COMPTEL (Schönfelder et al. 2000), and the 2σ upper limit is $1.7 \times 10^{-5} \text{ ph cm}^{-2}\text{s}^{-1}$. It is, however, prudent to allow for a 10% systematic uncertainty in the flux calibration. Note that without a detection, the exclusion of narrow line emission ultimately depends on the accuracy with which the overall $^{44}\text{Ti}$ emission is known. The planned observations of Cas A by INTEGRAL will help therefore in two ways: On the one hand IBIS-ISGRI will allow us to make more reliable total flux estimates, on the other hand SPI will provide either more stringent upper limits, which will help to constrain the line broadening, or a detection, in which case one can actually measure the line broadening.

4. Concluding remarks

Gamma-ray line emission from explosive nucleosynthesis products provides a view of what happens deep inside supernova explosions. Explosion asymmetries and turbulence during the explosion can be deduced from the time of emergence, and Doppler broadening of line emission from the short lived radioactive elements $^{56}\text{Ni}$ and $^{56}\text{Co}$. The longer lived radioactive element $^{44}\text{Ti}$ can be used to probe the explosion within a few hundred years after the supernova event. Although, $\gamma$-ray astronomy is a specialized field, its results are of general astrophysical importance, as the nature of both Type Ia and core-collapse supernovae are not well understood. This is even more important now that Type Ia supernovae are used to probe the history and fate of the universe, and gamma-ray bursts appear to be connected with core-collapse supernovae.

I have shown that $\gamma$-ray-astronomy has already fulfilled part of its promise. The detection of $^{56}\text{Co}$ lines from SN 1987A has provided us with clues about the mixing of supernova ejecta, although the theoretical understanding of the observations is not yet complete. The detection of $^{44}\text{Ti}$ from Cas A by COMPTEL and BeppoSAX, on the other hand, suggests that theoretical models underpredict the $^{44}\text{Ti}$ yield.

The work that started with SMM, COMPTEL and BeppoSAX-PDS and other experiments is continued with ESA’s INTEGRAL mission. For the more distant future several satellite missions are envisioned ranging from focusing telescopes, using grazing incidence telescopes with multilayer coating, von Laue lenses (i.e. using Bragg-crystals von Ballmoos et al. 2004), or a new Compton telescope (Kurfess 2004).

At the time of this writing INTEGRAL is in its second observing cycle, having already produced the first results on 511 keV, $^{26}\text{Al}$, and $^{44}\text{Ti} \gamma$-ray line emission, which will be
improved upon in the near future. And with some luck a not too distant Type Ia supernova may produce detectable γ-ray line emission, or, we might even be as lucky as Tycho Brahe and Johannes Kepler and observe a Galactic supernova.

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