Gamma-ray line diagnostics of supernova explosions - SN2014J and Cas A

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Abstract. Gamma-rays from nuclear de-excitation of newly produced isotopes during supernovae (SNe) provide a unique window to the explosion mechanisms. SNe interiors are accessible only by \( \gamma \)-rays as they are energetic enough to penetrate the SN cloud. Both thermonuclear explosions (type Ia) and core-collapse SNe (CCSN, type II) are key producers of heavy elements in the Universe. In SNe Ia, a white dwarf (WD) is disrupted by ignition from inside or by triggering the explosive event from outside, producing major amounts of \( ^{56}\text{Ni} \). Type II SNe are powered by the gravitational collapse of a massive star, having burnt all its nuclear fuel.

In this work, we present a diagnostic study of \( \gamma \)-ray lines from SN2014J and Cassiopeia A (Cas A). INTEGRAL observed SN2014J for several months and for the first time, it was possible to measure the characteristic lines from the \( ^{56}\text{Ni} \)-decay chain in a SN Ia event. Surprisingly, \( ^{56}\text{Ni} \) was seen only 20 days after the explosion which indicates that some \( ^{56}\text{Ni} \) must be located outside the WD and not deeply embedded. We provide a \( ^{56}\text{Co} \) \( \gamma \)-ray line light curve and estimate a visible \( ^{56}\text{Ni} \) mass of 0.5 M\( _{\odot} \) from a comparison to 1D model light curves. Cas A observations have been revisited and we detect both, the characteristic hard X-ray line from the decay of \( ^{44}\text{Ti} \) at 78 keV, and the subsequent \( \gamma \)-ray line from the decay of \( ^{44}\text{Sc} \) at 1157 keV in one coherent data set. Expansion velocities in the range of 2000 – 5000 km s\(^{-1} \) and an initially synthesised \( ^{44}\text{Ti} \) mass of \( 1.37 \times 10^{-4} \) M\( _{\odot} \) are found.

1. Introduction

A SN is the final fate of a star, producing major amounts of iron-peak and also heavier elements. When a massive star (\( \gtrsim 8 \) M\( _{\odot} \)) starts to lack of nuclear fuel in its interior, the radiation pressure cannot sustain gravitation any more and the Fe/Ni-core of the star collapses. The outer layers, consisting of lighter elements than Fe and Ni, are free-falling towards the centre and interact with the supernova shock wave, backbouncing from the newly build proto-neutron star. If this shock wave is energetic enough, it can accelerate the outer layers of stellar material up to the escape velocity which is called a CCSN. In the interaction region of shock wave and outer layers, explosive nucleosynthesis occurs and produces predominantly \( ^{56}\text{Ni} \) as the most stable nuclear configuration. This is described by nuclear statistical equilibrium for the short time of explosive burning. However, as the explosion site dilutes, other nuclear reactions are in favour, falling out of the equilibrium. In this case, an overabundance of \( \alpha \)-particles easily produces \( \alpha \)-multiple nuclei, e.g. \( ^{44}\text{Ti} \). This is known as \( \alpha \)-rich freeze-out [1, 2, 3, 4, 5, 6].

In contrast to massive stars, a SN Ia involves a WD that is triggered to explode by various mechanisms. There are two commonly accepted scenarios to disrupt the electron-degenerate matter of which a WD consists of: The single degenerate branch describes a WD and a giant star orbiting each other. Binary mass transfer due to Roche-lobe overflow gradually accretes mass from the giant companion star onto the
WD, building another layer of material. If C and/or O is accreted, the WD can reach its Chandrasekhar limiting mass and ignites in one more spots of its interior. A thin flame is rushing through the WD, totally disrupting it and producing new elements of which \(^{56}\text{Ni}\) has the largest fraction with \(0.1 - 1.0\, \text{M}_\odot\). If there is a He layer accreted, it can ignite in a flash and trigger the WD explosion from outside. The double-degenerate scenario explains a type Ia SN as the merger of two WDs, if they are not fusing to a neutron star [7, 8, 9, 10, 11, 12, 13, 14].

In both cases, the temporal and the spectral behaviour of \(\gamma\)-ray lines from various decaying isotopes can give deeper insights into the kinematics of the explosion and provide hints for the progenitor channels. Kinematic characteristics are reflected by the \(\gamma\)-ray line parameters, such as the line centroid and width. The line centroid is interpreted as the bulk (line-of-sight) motion, while the width represents the spread of expansion velocities. The amount of produced elements is most directly measured through the total \(\gamma\)-ray line flux of a particular isotope. Tracking the history of the parameters can tighten interpretations when comparing to models. For example, \(^{56}\text{Ni}\) and its daughter nucleus \(^{56}\text{Co}\) have comparatively short half-life times of 6 d and 77 d, respectively, and are therefore suitable to follow the very early phases of a supernova explosion. On the other hand, \(^{44}\text{Ti}\) has a half-life time of 60 a which makes studies of the interiors of considerably older SN remnants (SNRs) possible [15, 16, 17, 18, 19].

Utilizing two examples, one CCSN (Cas A [20]) and one SN Ia (SN2014J [21, 22]), we illustrate the necessity and capabilities of \(\gamma\)-ray line diagnostics for explosive stellar events. Gamma-rays originating in nuclear decay reaction open up a unique window into the deep interiors of SNe by ”X-raying it with \(\gamma\)-rays”. For SN2014J, we focus on the decay chain \(^{56}\text{Ni} \rightarrow ^{56}\text{Co} \rightarrow ^{56}\text{Fe}\), in which \(^{56}\text{Ni}\) decays to an excited state of \(^{56}\text{Co}\) which is predominantly emitting \(\gamma\)-rays of energies 158 keV and 812 keV when de-exciting to its ground state. Similarly, \(^{56}\text{Co}\) is decaying to stable \(^{56}\text{Fe}\), producing \(\gamma\)-rays at 847 keV and 1238 keV. In Cas A, most of the \(^{56}\text{Ni}\) and \(^{56}\text{Co}\) already decayed and the dominant energy provider are \(\gamma\)-rays from the decay chain \(^{44}\text{Ti} \rightarrow ^{44}\text{Sc} \rightarrow ^{44}\text{Ca}\). \(^{44}\text{Ti}\) is decaying to \(^{44}\text{Sc}\), emitting X-rays at 68 keV and 78 keV, followed by a \(\beta^+\)-decay of \(^{44}\text{Sc}\) to stable \(^{44}\text{Ca}\) only 3.9 h after, emitting \(\gamma\)-rays at 1157 keV. Radioactive decay \(\gamma\)-rays from the \(^{56}\text{Ni}\)-decay chain are what powers the light-curves in SNe Ia as they are absorbed in the SN could and re-emitted at lower energies. Likewise, \(\gamma\)-rays from the \(^{44}\text{Ti}\)-decay chain (and positrons) power the late light curve of CCSNe [23, 16].

2. Data Description and Analysis

Our observations have been made with the \(\gamma\)-ray spectrometer SPI aboard ESA’s INTEGRAL satellite. SPI is a coded-mask telescope, consisting of a honeycomb shaped array of 19 high-purity Ge detectors, measuring \(\gamma\)-rays with energies between 20 keV and 8 MeV at a resolution of 2.2 keV at 662 keV, and a segmented W mask 1.71 m above the array with partly opaque and partly transparent elements. Depending on the SPI pointing direction, a celestial \(\gamma\)-ray source imprints a certain shadowgram on the detector array which has to be discriminated against a large instrumental background, making typically 99% of the total counts. In order to create distinct sequences of patterns from celestial sources, the telescope is redirected around the target position, typically every half an hour by ~ 2° (dithering). The background patterns needed to build a self-consistent description of the measured data are essentially constant for particular, distinguishable physical sources in the spacecraft. They are determined by an elaborate spectral fitting procedure on time scales long enough to obtain statistical accuracy but at the same time short enough to trace detector degradation effects due to cosmic ray bombardment. Each instrumental background line is characterised by four line-shape parameters for each detector and for each time interval that is chosen (three days). The background continuum is treated separately as it exhibits a congeries of physical processes. Therefore, on longer time-scales, the detector patterns for the two background components \(\text{lines}\) and \(\text{continuum}\), and also for proposed (modelled) celestial sources, are fixed and need to be renormalised to the actual data. This is done by a maximum likelihood fit for each energy bin, estimating intensity scaling paramters for sky and background models simultaneously [24, 25, 26, 27, 28, 29]. Details for the whole procedure can be found in [21], [22], [20], and [30], for example; see also [31].
SN2014J occurred on January 2014, UT 14.75 ± 0.21 in the starburst galaxy M82 at a distance of 3.3 Mpc, \((l/b) = (141.43^\circ/40.56^\circ)\), and was recognised the closest type Ia event since four decades. It provided a unique opportunity to study such an event by its emitted \(\gamma\)-rays. INTEGRAL observed SN2014J between January 31 and June 26 2014, corresponding to days 16.3 and 164 after the explosion, with a total exposure time of \(\sim 7\) Ms [32, 33, 34, 35].

Cas A is a young CCSNR at a distance of 3.4 kpc in the Galactic plane, \((l/b) = (111.74^\circ/−2.13^\circ)\), and was targeted several times by INTEGRAL during its ongoing mission. Our data set formally comprises ten years of data, in which Cas A was seen with an exposure of 10.8 Ms in SPI's field of view (16\(^\circ\) × 16\(^\circ\)) [36, 37, 38, 39].

Given the angular resolution of SPI of \(\sim 2.7^\circ\), both sources are treated as point-sources in our analysis.

3. Results and Interpretation

3.1. SN2014J

Figure 1 shows the measurements of the early phase after the explosion of SN2014J, i.e. from days 16 to 34. The two most prominent \(\gamma\)-ray lines from the \(^{56}\text{Ni}\)-decay at 158 keV and 812 keV, are detected only 18 days after the explosion (Figs. 1a and 1b). The measured line fluxes are \((1.10 \pm 0.42) \times 10^{-4}\) ph cm\(^{-2}\) s\(^{-1}\) (158 keV) and \((1.90 \pm 0.66) \times 10^{-4}\) ph cm\(^{-2}\) s\(^{-1}\) (812 keV). The line centroids are 159.43 ± 0.43 keV and 811.84 ± 0.42 keV, consistent with the laboratory energies (2\(\sigma\)). The lines are not broadened which suggests velocity spreads (expansion velocities) of less than 2000 km s\(^{-1}\) (2\(\sigma\)). Within measurements uncertainties, the two lines are identical. Following the two \(\gamma\)-ray lines over a longer period substantiates the finding of \(^{56}\text{Ni}\) measured early in SN2014J as the measured light curves for both lines (see Fig. 1c) are consistent with the half-life time of \(\sim 6\) days for \(^{56}\text{Ni}\).

![Figure 1: \(^{56}\text{Ni}\)-measurements.](image)

Measuring decaying \(^{56}\text{Ni}\) that early for a type Ia is surprising as \(^{56}\text{Ni}\) is expected to be buried deeply in the SN cloud during that time. The visible mass of \(^{56}\text{Ni}\) 18 days after the explosion is estimated to be \((0.06 \pm 0.03)\) M\(_{\odot}\). Our interpretation is that some fraction of the \(^{56}\text{Ni}\) must be located near the surface of the WD. A possible though speculative configuration to explain this amount of \(^{56}\text{Ni}\) and to meet the kinematic constraints from the \(\gamma\)-ray measurements, which is unexpected in most explosion models, is as follows: If a He belt is accreted from a donor star, exploding, and triggering the explosion of the WD, the \(\gamma\)-ray data constraints can be met if this scenario is essentially seen pole-on. A He belt rather than a layer can be conserved if the accretion rate is of the order \(10^{-5}\) M\(_{\odot}\) a\(^{-1}\) and/or if the WD is rapidly rotating so that the accretion is faster than it loses angular momentum. Furthermore, radiation transfer...
simulations produce almost indistinguishable spectra in UVOIR wavelengths, when comparing standard scenarios to our proposed configuration. This makes SN2014J appear rather normal in these wavelength observations, although there are also hints for irregularities [21, 40, 35, 41, 42, 43, 44].

Figure 2 shows the measurements of decaying $^{56}\text{Co}$ from the position of SN2014J. During the $\gamma$-ray maximum around days 60-100, both major $\gamma$-ray lines originating in the decay of $^{56}\text{Co}$ at 847 keV and 1238 keV are clearly detected (Figs. 1a and 1b). Obtained flux values are $(3.7 \pm 1.2) \times 10^{-4}$ ph cm$^{-2}$ s$^{-1}$ (847 keV) and $(2.3 \pm 0.7) \times 10^{-4}$ ph cm$^{-2}$ s$^{-1}$ (1238 keV), respectively. This can directly be converted to an initially synthesised $^{56}\text{Ni}$ mass seen to decay of $(0.49 \pm 0.12)$ M$_{\odot}$. The lines are Doppler-broadened and suggest expansion velocities of $7250 \pm 1500$ km s$^{-1}$. This is in concordance with most explosion models.

Figure 2: $^{56}\text{Co}$-measurements. Left and middle panel show the spectra (black crosses) from the position of SN2014J about 80 days after the explosion with a Gaussian line fitted to the data points. The right panel shows the 847 keV $^{56}\text{Co}$ $\gamma$-ray line light curve with time resolutions of $\sim 30$ days (red) and $\sim 10$ days (blue). There are theoretical 1D $\gamma$-ray line light curves exemplified, taken from [45].

In Fig. 2c, the $\gamma$-ray line light curve for the 847 keV line during INTEGRAL observations is illustrated. The line flux shows a rise in intensity towards the $\gamma$-ray maximum and a decline consistent with the half-life time of $^{56}\text{Co}$, as expected. However, utilizing the fine energy resolution of SPI and a smaller time binning reveals discrepancies between the theoretical, smooth behaviour during the rise to the maximum, which may indicate asymmetries in the explosion or shadowing effects in the morphology (blue data points). The spectra for all epochs, except after day 134, indicate aspherical $^{56}\text{Ni}$ distributions, perhaps caused by clumps or co-moving volume elements at certain times, occulting the $\gamma$-ray signal. By testing several 1D models from [45], we independently estimate the synthesised $^{56}\text{Ni}$ mass to $(0.49 \pm 0.12)$ M$_{\odot}$, formally favouring models with He near the surface of the SN. Acceptable fits provide $^{56}\text{Ni}$ masses between 0.4 and 0.8 M$_{\odot}$, and we want to emphasise that these estimates are based on 1D models which assume single and smoothly broadened gaussian lines. This may not be reflected by our data and estimates should be taken with caution. Despite the clear detection of $^{56}\text{Ni}$ and $^{56}\text{Co}$ $\gamma$-ray lines, a thorough statistical discrimination among progenitor models is inadequate and most models are in agreement with our $^{56}\text{Ni}$ measurements if the $^{56}\text{Ni}$ mass is a free parameter [22, 45, 46, 47].

3.2. Cas A
SPI allows one to measure the whole $^{44}\text{Ti}$-decay chain using the same instrument in one coherent data set. Figures 3a and 3b show the spectra from the position of Cas A about 340 years after the estimated explosion date in AD 1681. The 78 keV X-ray line form the decay of $^{44}\text{Ti}$ has a total flux of $(2.1 \pm 0.4) \times 10^{-5}$ ph cm$^{-2}$ s$^{-1}$, is centred at 78.9 $\pm$ 1.5 keV and broadened 1.9 $\pm$ 0.6 keV above the instrumental resolution. These values lead to a $^{44}\text{Ti}$ mass estimate of $(1.5 \pm 0.4) \times 10^{-4}$ M$_{\odot}$ seen to decay, and an estimate for the velocity spread of $4300 \pm 1600$ km s$^{-1}$ at essentially no bulk motion. Due to
complications in modelling background features below $\sim 73$ keV, increasing the background level by two orders of magnitude, the 68 keV line is not detected. The flux from $\gamma$-ray line at 1157 keV from the subsequent decay of $^{44}\text{Sc}$ is $(3.5 \pm 1.2) \times 10^{-5}$ ph cm$^{-2}$ s$^{-1}$, and is centred at 1158.0 $\pm$ 3.6 keV and broadened by 8.9 $\pm$ 1.4 keV. Although the $^{44}\text{Ti}$ mass estimate is considerably larger, $(2.4 \pm 0.9) \times 10^{-4}$ M$_\odot$, the expansion velocity estimate of the ejecta is only 2200 $\pm$ 400 km s$^{-1}$.

Figure 3: $^{44}\text{Ti}$- and $^{44}\text{Sc}$-measurements. Left and middle panel show the spectra (black crosses) from the position of Cas A measured with SPI with a Gaussian line fitted to the data points. The right panel shows $^{44}\text{Ti}$ and $^{44}\text{Sc}$ measurements from this work (SPI) as well as previous measurements with other instruments. The data points for each $\gamma$-ray line have been fitted with an exponential decay function, separately, revealing a flux discrepancy between $\gamma$-rays originating in excited $^{44}\text{Sc}$ and excited $^{44}\text{Ca}$.

This apparent discrepancy becomes even more significant when measurements from earlier instruments are included in the analysis (see Fig. 3c). The measurements for the high-energy line at 1157 keV (COMPTEL and SPI) show a systematically higher flux value, compared to the low-energy line measurements from OSSE, BeppoSAX, ISGRI, SPI, and NuSTAR, although the values should be almost equivalent 340 years after the explosion. We argue that the true kinematics of the Cas A SNR are reflected in the line shapes originating in the decay of $^{44}\text{Ti}$ to $^{44}\text{Sc}$*, emitting 68 keV and 78 keV X-rays. The second step in the decay chain, from $^{44}\text{Sc}$ to $^{44}\text{Ca}$*, may not be the only process that leads to excited $^{44}\text{Ca}$ because low-energy cosmic rays are believed to be able to excite ambient $^{44}\text{Ca}$ which promptly emits 1157 keV $\gamma$-rays. As $^{44}\text{Sc}$ is decaying with a half-life time of only 3.9 h, no $^{44}\text{Sc}$ is available to be excited efficiently enough to produce additional flux in the low-energy lines. Under this assumption, i.e. by combining only the low-energy line measurements, the $^{44}\text{Ti}$-mass estimate is $(1.28 \pm 0.14) \times 10^{-4}$ M$_\odot$, and an additional flux level of $(2.3 \pm 0.6) \times 10^{-5}$ ph cm$^{-2}$ s$^{-1}$ is revealed for the 1157 keV line. Although this effect is expected, the measured magnitude is 10-100 times larger than from theoretical estimates. Combining all previous measurements without any assumptions obtains an estimate for the initially synthesised $^{44}\text{Ti}$-mass of $(1.37 \pm 0.19) \times 10^{-4}$ M$_\odot$ [20, 48, 49, 50, 51, 52, 53, 54, 55, 56].

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