Gamma-Ray Line Astrophysics and Stellar Nucleosynthesis: Perspectives for INTEGRAL

N. Prantzos

Institut d'Astrophysique de Paris

ABSTRACT Nuclear γ-ray lines constitute the most genuine diagnostic tool of nuclear astrophysics, since they allow for an unambiguous identification of isotopic species. Continuous improvement in instrumentation led to the discovery of several radioactive species in the past 15 years (^{26}Al, ^{56}Co, ^{57}Co, ^{44}Ti) in various astrophysical sites (SN1987A and SN1991T, Cas-A, the Milky Way disk). These discoveries boosted theoretical activity on the nucleosynthesis of these radioactive isotopes and on the refined modelling of the corresponding sites, improving our knowledge on stellar evolution, stellar explosions, galactic structure, etc. I review here the current status of γ-ray line astrophysics and present some perspectives related to stellar nucleosynthesis, in view of future missions like $INTEGRAL$ (for more detailed recent reviews see also Prantzos 1996; and Diehl and Timmes 1998).

KEYWORDS: Stellar nucleosynthesis - supernovae - γ-ray lines

1. INTRODUCTION

The most important cosmic radioactivities for γ-ray line astronomy are presented in Table 1, along with the corresponding lifetimes, energies, branching ratios, nucleosynthetic processes, astrophysical sites of production and sites of detection (as of 1998).

The decay lifetime plays a determining role in the detectability of a radioactive nucleus. All nuclei are synthesized in high density environments, initially opaque to γ-rays. The photons of their decays interact with the surrounding material and are Compton-scattered down to X-ray energies, until they are photoelectrically absorbed and their energy is released at longer wavelengths. Only in the case of a site violently expanding after the explosion (SN, novae) or suffering extensive mass loss (WR and AGB stars) do the γ-ray lines have a chance to emerge, since the opacity decreases with decreasing density. For instance, the timescale for the supernova ejecta to become transparent is such (a few weeks for SNIa, $\sim$1 yr for SNII) as to make essentially undetectable the γ-ray lines of the short-lived ^{56}Ni.

The intensity of the escaping γ-ray lines gives important information on the yields of the corresponding isotopes and the physical conditions (temperature, density, neutron excess etc.) in the stellar zones of their production. The shape of the γ-ray lines reflects the velocity distribution of the ejecta, modified by the opacity along the line of site and can give information on the structure of the ejecta (see e.g. Burrows 1991 for the potential of γ-ray lines as a tool of supernova diagnostics). Up to now, only the ^{56}Co lines from SN1987A and the ^{26}Al line from the inner Galaxy have been resolved (both with the same instrument, the GRIS Ge spectrometer), but their "message" is not quite understood yet.

TABLE 1: COSMIC RADIOACTIVITIES AND γ-RAY LINES

DECAY CHAIN	MEAN LIFE* (yr)	LINE ENERGIES (MeV)	SITE [Detected]	PROCESS
^{56}Ni$\rightarrow^{56}$Co$\rightarrow^{56}$Fe	0.31	$\underline{0.847}$ (1.) $\underline{1.238}$ (0.685) 2.598 (0.17) 1.771 (0.45)	SN [SN1987A] [SN1991T]	NSE
^{57}Co$\rightarrow^{57}$Fe	1.1	$\underline{0.122}$ (0.86) $\underline{0.136}$ (0.11)	SN [SN1987A]	α-NSE
^{22}Na$\rightarrow^{22}$Ne	3.8	1.275 (1.)	Novae	$Ex.$H
^{44}Ti$\rightarrow^{44}$Sc$\rightarrow^{44}$Ca	90	$\underline{1.156}$(1.) 0.068 (1.) 0.078 (0.98)	SN [CasA]	α-NSE
^{26}Al$\rightarrow^{26}$Mg	1.1 10^6	$\underline{1.809}$ (1.)	WR, AGB Novae SNII [Galaxy]	$St.$H $Ex.$H $St. + Ex.$Ne ν
^{60}Fe$\rightarrow^{60}$Co$\rightarrow^{60}$Ni	2.2 10^6	1.322 (1.) 1.173(1.)	SN	n-NSE

*: For double decay chains the longest lifetime is given;

Underlined: lines already detected;

Numbers in *parentheses*: branching ratios; In *brackets*: sites of lines detected

St.: Hydrostatic burning; *Ex.*: Explosive burning; NSE: Nuclear statistical equilibrium

α: α-rich "freeze-out"; n-: normal "freeze-out"; ν: neutrino-induced nucleosynthesis

When the lifetime of a radioactive nucleus is not very large w.r.t. the timescale between two nucleosynthetic events in the Galaxy, those events are expected to be seen as point-sources in the light of that radioactivity. In the opposite case a diffuse galactic emission is expected from the cumulated emission of many sources. Characteristic timescales between two explosions are ~1-2 weeks for novae (from their estimated Galactic frequency of ~30 yr^{-1}, Della Vale and Livio 1994), ~40 yr for SNII+SNIb and ~300 yr for SNIa (from their corresponding Galactic frequencies, Tammann et al. 1994). Comparing those timescales to the decay lifetimes of Table 1 one sees that in the case of the long-lived ^{26}Al and ^{60}Fe a diffuse emission is expected; the spatial profile of that emission should reflect the Galactic distribution of the underlying sources (except if high velocity ejecta can travel undecelerated for long times; see Sec. 4). The other radioactivities of Table 1 should be seen as point sources in the Galaxy except, perhaps, ^{22}Na from Galactic novae; indeed, O-Ne-Mg rich novae have a frequency ~1/3 of the total resulting in ~40 sources active in the Galaxy during the lifetime of ^{22}Na.

2. Co IN SN1987A, SN1991T (AND EXTRAGALACTIC SNIa WITH *INTEGRAL*?)

The appearence of SN1987A in the closeby LMC confirmed in a spectacular way early ideas about the synthesis of radioactive nuclei in supernovae; in particular, it confirmed that ^{56}Fe, the most strongly bound stable nucleus in nature, is produced in the form of the unstable species ^{56}Ni. The main points of relevance to γ-ray line astronomy are as follows:

1) The definitive confirmation of the ^{56}Co synthesis came from the detection of the 0.847 MeV and 1.238 MeV lines of its radioactive decay (Matz et al. 1988). Their appearance $\sim$6 months earlier than expected suggested that mixing and/or fragmentation had taken place in the mantle of SN1987A during the explosion or shortly after, bringing heavy nuclei from the inner layers into the outer ones. This discovery convincingly demonstrated that the explosion does not preserve the stratification of the onion-skin layers of the pre-supernova star. Prompted by this observation, hydrodynamical 2-D and 3-D calculations found that mixing does indeed take place, due mostly to Rayleigh-Taylor type instabilities (e.g. Hashisu et al. 1990, Fryxel et al. 1991). That discovery was a major contribution of γ-ray line astronomy to our understanding of supernova explosions.

2) The profile of the 0.847 MeV and 1.238 MeV lines, resolved by the GRIS balloon-born instrument (Tueller et al. 1991) remains poorly understood up to now. The lines are red-shifted by 500-800 km s^{-1} (contrary to what is expected from an optically thick source) and their width is larger than predicted from theory (indicating that some fraction of ^{56}Co has penetrated deeply in the high velocity H-rich envelope). Despite some preliminary models (Grant and Dean 1993; Barrows and van Riper 1995), a convincing explanation does not exist yet.

3) The previous results were obtained before the CGRO launch. The discovery by OSSE of the 122 keV and 136 keV lines due to the decay of ^{57}Co (Kurfess et al. 1992) is the major contribution of CGRO in our understanding of SN1987A. The detected flux corresponds to a mass of $\sim$2.7 10^{-3} M$_\odot$ of ^{57}Co. This leads to a production ratio ^{57}Ni/^{56}Ni= 1.4$\pm$0.35 times the solar ratio of the daughter stable nuclei (^{57}Fe/^{56}Fe)$_\odot$, suggesting an important contribution from "α-rich" freeze-out, i.e. that most of ^{57}Co was produced in relatively low-density environment (Clayton et al. 1992). Moreover, the OSSE measurement ruled out earlier suggestions about the late lightcurve of SN1987A being powered by a larger amount of ^{57}Co; recent analysis of the latest UVBRIJHK lightcurves show that the required ratio (57/56)$\sim$2 times solar is compatible with γ-ray measurements (Fransson and Kozma 1998).

The extraordinary chance offered by SN1987A was due to its proximity; had it been in the Andromeda galaxy, it would have been undetectable by instruments of the 80ies and 90ies and marginally detectable by an *INTEGRAL*-type instrument. This is due to the fact that γ-ray photons from massive star explosions have to wait for a long time before escaping, i.e. until the opacity of the $\sim$10 M$_\odot$ slowly expanding envelope drops to sufficiently low levels. Much more interesting in that respect are SNIa: their small envelopes ($<$1 M$_\odot$) and large expansion velocities ($>$1.5 10^4 km/s), combined to the large amounts of produced ^{56}Ni ($\sim$0.5-1. M$_\odot$, typically ten times the average SNII yield), make their ^{56}Co lines thousands of times brighter than those of SNII. The ^{56}Co lines of SNIa are detectable up to the Virgo cluster of galaxies (∼13-20 Mpc) by instruments with a sensitivity of $\sim 10^{-5}$ cm^{-2} s^{-1}, i.e. close to the sensitivity limit of CGRO.

SN1991T, a bright SNIa, exploded in the spiral galaxy NGC4527, at the periphery of the Virgo cluster and at an estimated distance of 17 Mpc. An analysis of the COMPTEL data for two observations 66 and 176 days after the explosion, shows evidence for the 847 and 1238 keV lines of ^{56}Co. The obtained line flux (Morris et al. 1995) corresponds to a rather large amount of ^{56}Ni($>$1.3 M$_{\odot}$ for a distance of $>$13 Mpc), implying that almost all of the white dwarf turned into ^{56}Ni. Sub-Chandrasekhar mass models for SNIa (with a detonation in the base of the accreted helium layer inducing a further detonation inside the white dwarf), or delayed detonation models (where the flame front propagates subsonically at large distances from the center of the white dwarf before turning into a detonation) may explain an early detection of the γ-ray lines, but perhaps not such large amounts of ^{56}Ni. More detections of extragalactic SNIa are required to clarify how typical SN1991T was and before further conclusions are drawn.

SN1991T illustrates the kind of diagnosis of SNIa models that can be achieved through the analysis of their ^{56}Co lines. A detailed exploration of the potential of this method has been recently performed (Höflich et al. 1998, Gomez-Gomar et al. 1998). However, statistical analysis show that the perspectives of detecting SNIa with *INTEGRAL* are rather dim, since its sensitivity to broad lines (expected from the high velocity ejecta of SNIa) is not much better than that of CGRO (for recent estimates see Timmes and Woosley 1997; and Isern, this volume).

3. ^{44}Ti FROM CAS-A, GRO J0852-4642 (AND SN1987A WITH *INTEGRAL* ?)

The half-life of ^{44}Ti has been surprisingly uncertain in the past 20 years, with measured values ranging from 39 to 66 years. These discrepant results and the difficulty in measuring the ^{44}Ti lifetime are due to the fact that the number of ^{44}Ti nuclei one can obtain is small (w.r.t. the Avogadro number), while the ^{44}Ti lifetime is large w.r.t. the available laboratory time. The recent measurements of three different groups, however, seem to convincingly converge towards a value of 60±1 years (Görres et al. 1998, Ahmad et al. 1998, Norman et al. 1998).

The lifetime of ^{44}Ti is comparable to the characteristic timescale between two supernova explosions in the Milky Way, so that the resulting γ-ray line emission should appear as point sources in the Galaxy. On the other hand, the ^{44}Ti lifetime is sufficiently long to make it an excellent probe of Galactic supernova explosions in the past few centuries, since its γ-ray lines may reveal supernova remnants undetected in other wavelengths up to now (as has been demonstrated by the recent detection of 1.16 MeV emission from the previously unknown and presumably nearby SNR GRO J0852-4642; see Iyudin et al. 1998)

CasA is one of the youngest and closest known supernova remnants at a distance of ∼3 kpc. Its age is evaluated to $>$300 yr from extrapolation of the remnant's expansion to the origin. Despite its proximity and high declination the explosion was not reported in the 1600's. Optical and X-ray measurements suggest that the progenitor was a 20 $M_\odot$ WR star, that exploded as an underluminous SNIb.

The COMPTEL team reported the detection of the 1.16 MeV line of ^{44}Ti, with a flux of 4.2$\pm$0.9 10^{-5} cm^{-2} s^{-1}(Iyudin et al. 1997) compatible with the upper limit reported by the OSSE team (5 10^{-5} cm^{-2} s^{-1}, The et al. 1995). This translates into a mass of ^{44}Ti produced by the explosion of $\sim$1.5 10^{-4} $M_\odot$ i.e. not too far from theoretical predictions.

However, the CasA detection brought forward an unexpected puzzle. Since both ^{44}Ti and ^{56}Ni are synthesized in the same stellar zones, the inferred amount of ^{44}Ti corresponds to a mass of ^{56}Ni of $\sim$0.05 $M_\odot$. Powered by the ^{56}Ni decay, the supernova (with or without a hydrogen envelope) would have then a peak magnitude M_V <-4 at 3 kpc (The et al. 1995). CasA should have been a rather bright supernova for a few weeks, making it difficult to understand why it went unreported. Some 10 magnitudes of visual extinction are required to make the ^{44}Ti observation consistent with the absence of historical records for that supernova.

Among the various proposed solutions to the puzzle, the most natural seems to be the one invoking a dusty shell of material (ejected by the winds of the progenitor star) hiding CasA during the explosion; the supernova shock wave would have destroyed later most of the dust, as it propagated through the debris, explaining the currently dust-free environment of CasA (Hartmann et al. 1997).

Notice that ^{44}Ti is the third radioactivity that will, someday, be discovered in SN1987A. Along with ^{57}Co it is produced in the hottest and deepest layers ejected during the explosion of a massive star. The ejected quantity is very sensitive to the position of the "mass-cut" (i.e. the line dividing the supernova ejecta from the matter accreted onto the compact object). Nucleosynthesis calculations for SN1987A show that $\sim$1.5 10^{-4} $M_\odot$ of ^{44}Ti were synthesized by the explosion (e.g. Thielemann et al. 1996); similar amounts are suggested from the fitting of the late lightcurve of SN1987A, if it is indeed powered by ^{44}Ti (Fransson and Kozma 1997). Such amounts of ^{44}Ti produce on Earth a flux of $\sim$3 10^{-6} cm^{-2} s^{-1} in the 68, 78 and 1157 keV lines for many decades after the explosion. If ^{44}Ti is ejected at low speed ($\sim 10^3$ km/s, as suggested by spherically symetric models of the explosion of SN1987A), the kinetic broadening of the lines will be small and the estimated fluxes close to the sensitivity limit of *INTEGRAL* for narrow lines. ^{44}Ti from SN1987A will then certainly be a prime target for that satellite; its detection will allow to probe the deepest ejected layers of SN1987A better than ever before.

4. ^{26}Al IN THE GALACTIC PLANE (AND ^{60}Fe WITH *INTEGRAL*?)

^{26}Al is the first cosmic radioactivity ever detected in γ-rays, through its characteristic 1.8 MeV line. Its detection by the HEAO-3 satellite (Mahoney et al. 1982) clearly shows that nucleosynthesis is currently active in the Galaxy and offers an unprecedented opportunity to identify the site of that activity. A recent review (Prantzos and Diehl 1996) discusses all aspects of ^{26}Al relevant to nucleosynthesis and γ-ray line astronomy.

The current status of ^{26}Al observations by COMPTEL is presented by Diehl (this volume). The data shows clearly a diffuse, irregular, emission along the Galactic plane, allowing to eliminate: i) a unique point source in the Galactic centre; ii) a strong contribution of the Galactic bulge, signature of an old population and iii) any class of sources involving a large number of sites with low individual yields (novae, low mass AGB stars), since a smooth flux distribution is expected in that case.

The irregular 1.8 MeV emission detected by COMPTEL along the galactic plane reveals, better than any other tracer, the sites of current nucleosynthetic activity in the Galaxy. A very tempting identification can already be made of several 1.8 MeV "hotspots" with tangents to the spiral arms (Diehl et al. 1995); as suggested by Prantzos (1993) such a correlation would imply that massive stars are at the origin of (most of) the derived $\sim$2.5 $M_{\odot}$ of galactic ^{26}Al.

In a recent work of multi-frequency image comparison, Knödlseder (1998) showed that a map of the ionisation power from massive stars (derived from the COBE data, after correction for synchrotron contribution) corresponds to the 1.809 MeV map of galactic ^{26}Al in all significant detail; assuming a standard stellar initial mass function, his calculation reproduces consistently the current galactic supernova rate and massive star population from both maps, and suggests that most of ^{26}Al is produced by WR stars of high metallicity in the inner Galaxy.

Two of the COMPTEL hotspots, at l$\sim$80^o and 90^o are certainly not related to spiral features (Cygnus superbubble, Vela region). Their detection will certaibly allow to probe better the underlying stellar populations and their ^{26}Al yields; notice that the 1.8 MeV Vela "hot-spot" is no more associated to the closeby Vela supernova remnant alone, as originally thought (Diehl 1998, this volume).

A recent intriguing development in the ^{26}Al "saga" concerns the spectral width of the 1.8 MeV emission from the inner Galaxy. The *GRIS* spectrometer resolved the 1.8 MeV line from that region (Naya et al. 1996), finding it larger (ΔE=5.4$\pm$1.4 keV keV) than what expected from galactic rotation ($\sim$1 keV). Even if ^{26}Al is initially ejected at high velocities, it is difficult at present to understand how it could go undecelarated during most of its 1 Myr lifetime. Among the several alternative hypotheses explored in Chen et al. (1997) the one of ^{26}Al being condensed in high-speed dust grains seems promising, but the *GRIS* measurement needs conformation, since it is incompatible with the *HEAO C* line width limit of $<$3 keV.

One of the most exciting perspectives for *INTEGRAL* in relation to ^{26}Al, is the possibility to detect a diffuse ^{60}Fe γ-ray emission at 1.2 and 1.3 MeV and give some hints as to its distribution in the Galaxy. Indeed, detailed SNII models (Woosley and Weaver 1995) give a ^{60}Fe yield $\sim$0.25-0.35 of the corresponding ^{26}Al yield when averaged over a reasonable stellar initial mass function. Taking into account their respective lifetimes (Table 1), the flux in the ^{60}Fe lines is expected to be $\sim$0.15 that of the galactic 1.8 MeV flux, *if* SNII are the major producers of Galactic ^{26}Al. If the ^{60}Fe lines are not detected by *INTEGRAL*, then nucleosynthesis in SNII should be seriously revised or (more radically) SNII should be discarded as major sources of ^{26}Al. In both cases a major information for stellar nucleosynthesis will be obtained.

TABLE 2: PERSPECTIVES FOR STELLAR γ-RAY LINES WITH *INTEGRAL*

ISOTOPE	LINE E(MeV)	TARGET	OBSERVABLE	INTEREST
^{56}**Co**	0.847 1.238	Extragalactic SNIa	Intensity Shape	Constrain models of SNIa
^{44}**Ti**	0.068 0.078 1.156	SN1987A	Flux	Nucleosynthesis Mass-cut
		CasA	Confirmation + Shape	$V_{EJ}\rightarrow$CasA Age + Models
		Galactic SN	Intensity + Shape	Models + Nucleosynthesis
^{26}**Al**	1.809	Galaxy	Accurate map Line width	Nucleosynthesis sites Ejecta propagation
		Galactic "Hot-spots" (e.g. Vela)	Line Shape Flux Extent	Distances Yields V_{EJ}
^{60}**Fe**	1.173 1.322	Galaxy	F$\sim$ 0.1 $F_{^{26}Al}$ (map ?)	Sources
^{22}**Na**	1.275	Novae	Flux, Shape	Models

5. SUMMARY AND PERSPECTIVES

Gamma-ray line astronomy became a privileged tool for the study of stellar nucleosynthesis in the past ten years; the proximity of SN1987A and the launch of CGRO played a major role in this rapid progress.

The detection of four cosmic radioactivities up to now (^{56}Co, ^{57}Co, ^{44}Ti, and ^{26}Al) allowed to probe in depth the supernova structure and the thermodynamic conditions of the explosion (with ^{56}Co and ^{57}Co in SN1987A), to confront simple supernova models to observations (with more success in SN1991T than in CasA) and to locate the sites of large scale nucleosynthetic activity in the Galaxy (through the irregular profile of the ^{26}Al emission).

The perspectives are even brighter, since the increased sensitivity of *INTEGRAL* will allow to explore further those issues and to tackle several other related topics. A synopsis of the most important perspectives for the study of stellar nucleosynthesis with *INTEGRAL* is presented in Table 2. Most of those perspectives are discussed in the previous sections. For those left outside this review, one should see the contributions by Hernanz et al. (for ^{22}Na from galactic novae) and Leising (for the galactic 511 keV line), in this volume.

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