STELLAR RADIOACTIVITIES AND DIFFUSE GAMMA-RAY LINE EMISSION IN THE MILKY WAY

N. PRANTZOS
Institut d’Astrophysique de Paris, 98bis Bd Arago,
75014 Paris, France

After a short historical introduction to the field of γ-ray line astronomy with radioactivities, I present an overview of recent results concerning the massive star yields of those radioactivities. I comment on the implications of those results (concerning long-lived radioactivities, like $^{26}$Al and $^{60}$Fe) for γ-ray line astronomy, in the light of past (COMPTEL and GRIS) and forthcoming (INTEGRAL) observations.

1 Introduction

Shortly after the discovery of the phenomenon of radioactivity, radionuclides revealed to be unique "probes" in our study of the cosmos and important agents in its evolution (radioactive dating of the Earth, meteorites and stars; radioactive heating of planetary and supernova interiors; radioactive origin of abundant stable nuclei, like $^{56}$Fe, and of isotopic anomalies in meteorites, etc).

As most other stable nuclei, radionuclides are produced in stellar interiors and ejected in the interstellar medium through stellar winds and explosions (nova or supernova). In a few cases, concerning extra-solar objects, the characteristic γ-ray line signature of their radioactive decay has been detected and used as a probe of a large variety of astrophysical sites; indeed, γ-ray line astronomy with cosmic radioactivities has grown to a mature astrophysical discipline in the last decade. See, e.g. Diehl and Timmes 1998, Arnould and Prantzos 1999, Knödlseder and Vedrenne 2001, for recent reviews; also, the proceedings of the Astronomy with Radioactivities Conference, organised every two years, nicely reflects the status of that discipline (web site: http://www.mpe.mpg.de/gamma/science/lines/workshops/radioactivity.htm).

In this review I shall focus on radioactivities produced by massive stars (SNII and WR stars); radioactivities produced by exploding white dwarfs (novae and SNIa) are reviewed by Hernanz (this volume).

2 A short history of stellar radioactivities and γ-ray line astronomy

The main theoretical ideas underlying γ-ray line astronomy emerged slowly in the 60ies, while observational evidence came only about 20 years later. This history is largely dominated by two rather independent “programmes” of research: an astronomical one, seeking for the explanation of the late lightcurves of supernovae, and a nucleosynthetic one, seeking for the origin of the most abundant heavy nucleus, $^{56}$Fe. An exceptionally clear and vivid account of that history is given in the text of Clayton (1999), on which much of this section is based.
In the early 50ies, the exponential decline of the late lightcurves of SNIa was attributed to the radioactive decay of $^7\text{Be}$ (Borst 1950) or $^{59}\text{Fe}$ (Anders 1959) or $^{254}\text{Cf}$ (Anders 1959, Burbidge et al. 1956), all those nuclei having half-lives of $\sim$45-55 days. In his PhD thesis (1962), the mineralogist T. Pankey Jr suggested that $^{56}\text{Fe}$ is produced as unstable $^{56}\text{Ni}$, and that the radioactive chain $^{56}\text{Ni}\rightarrow^{56}\text{Co}\rightarrow^{56}\text{Fe}$ can explain the lightcurves of supernovae; however, his suggestion went completely unnoticed by astronomers and nuclear physicists alike. Indeed, up to the mid-sixties it was thought that $^{56}\text{Fe}$ is produced as such in stellar interiors (Hoyle 1946; Burbidge et al. 1957; Fowler and Hoyle 1964), through the so-called “e-process”, despite the fact that the issue of its ejection in the interstellar medium (which might modify its abundance) was far from being clear. The role of explosive Si-burning, leading to the production (and natural ejection from supernovae) of doubly-magic $^{56}\text{Ni}$ was clarified through semi-analytical calculations of Bodansky et al. (1968), after hints from pioneering numerical nucleosynthesis calculations of Truran et al. (1966). Based on those results, Colgate and McKee (1969) convincingly argued that the radioactive chain $^{56}\text{Ni}\rightarrow^{56}\text{Co}\rightarrow^{56}\text{Fe}$ powers the lightcurves of supernovae; as time goes on, an increasing percentage of that power escapes the SN ejecta (which become progressively more transparent to $\gamma$-rays) and as a result the optical light curve declines more rapidly (by a factor of 2 every $\sim$55 days) than the amount of $^{56}\text{Co}$ (half-life: 77 days).

The implications of those ideas for $\gamma$-ray line astronomy were studied in the 60ies at the Rice University, where Clayton and Craddock (1965) first calculated the expected $\gamma$-ray flux and spectrum from the Crab remnant, on the assumption that the $^{254}\text{Cf}$ hypothesis was correct; finding that extremely large overabundances of other heavy elements (Os, Ir, Pt) should be obtained in that case, they expressed doubts on the correctness of that hypothesis. After this “false-start”, the implications of $^{56}\text{Ni}$ production in Si-burning were fully clarified in the landmark paper of Clayton, Colgate and Fishman (1969), which opened exciting perspectives to the field by suggesting that any supernova within the local group of galaxies should be detectable in $\gamma$-ray lines.

In the 70ies D. Clayton identified most of the radionuclides of astrophysical interest (i.e. giving a detectable $\gamma$-ray line signal); for that purpose he evaluated their average SN yields, by assuming that the corresponding daughter stable nuclei are produced in their solar system abundances. Amazingly enough (or naturally enough, depending on one’s point of view) his predictions of average SNII radionuclide yields (Table 2 in Clayton 1982) are in excellent agreement with modern yield calculations, based on full stellar models and detailed nuclear physics (see Fig. 1). Only the importance of $^{26}\text{Al}$ escaped Clayton’s (1982) attention, perhaps because its daughter nucleus $^{26}\text{Mg}$ is produced in its stable form, making the evaluation of the parent’s yield quite uncertain. That uncertainty did not prevent Arnett (1977) and Ramaty and Lingenfelter (1977) from arguing (on the basis of Arnett’s (1969) explosive nucleosynthesis calculations) that, even if only $10^{-3}$ of solar $^{26}\text{Mg}$ is produced as $^{26}\text{Al}$, the resulting Galactic flux from tens of thousands of supernovae (during the $\sim$1 Myr lifetime of $^{26}\text{Al}$) would be of the order of $10^{-4}$ cm$^{-2}$ s$^{-1}$.

In the case of $^{26}\text{Al}$ nature appeared quite generous, providing a $\gamma$-ray flux even larger than the optimistic estimates of Ramaty and Lingenfelter (1977): the HEAO-3 satellite detected the corresponding 1.8 MeV line from the Galactic center direction at a level of $4 \times 10^{-4}$ cm$^{-2}$ s$^{-1}$ (Mahoney et al. 1984). That detection, the first ever of a cosmic radioactivity, showed that nucleosynthesis is still active in the Milky Way; however, the implied large amount of galactic $^{26}\text{Al}$ ($\sim$3 M$_\odot$ per Myr, assuming steady state) was difficult to accommodate in conventional models of galactic chemical evolution if SNII were the main $^{26}\text{Al}$ source (Clayton 1984), since $^{27}\text{Al}$ would be overproduced in that case; however, if the “closed box model” assumption is dropped and infall is assumed in the chemical evolution model, that difficulty is removed, as subsequently shown by Clayton and Leising (1987).

Another welcome mini-surprise came a few years later, when the $^{56}\text{Co}$ $\gamma$-ray lines were de-
ected in the supernova SN1987A, a $\sim 20$ M$_{\odot}$ star that exploded in the Large Magellanic Cloud. On theoretical grounds, it was expected that a SNIa (expanding white dwarf of $\sim 1.4$ M$_{\odot}$ that produces $\sim 0.7$ M$_{\odot}$ of $^{56}$Ni) would be the first to be detected in $\gamma$-ray lines; indeed, the large envelope mass of SNI (\$10$ M$_{\odot}$) allows only small amounts of $\gamma$-rays to leak out, making the detectability of such objects problematic (Woosley et al. 1981, Gehrels et al. 1987). Despite the intrinsically weak $\gamma$-ray line emissivity of SN1987A, the proximity of LMC allowed the first detection of the tell-tale $\gamma$-ray line signature from the famous radioactive chain $^{56}$Ni $\rightarrow ^{56}$Co $\rightarrow ^{56}$Fe, thus confirming a 25-year old conjecture (namely, that the abundant $^{56}$Fe is produced in the form of radioactive $^{56}$Ni).

Those discoveries laid the observational foundations of the field of $\gamma$-ray line astronomy with radioactivities. The next steps were made in the 90ies, thanks to the performances of the Compton Gamma-Ray Observatory (CGRO). First, the OSSE instrument aboard CGRO detected the $^{57}$Co $\gamma$-ray lines from SN1987A (Kurfess et al. 1992); the determination of the abundance ratio of the isotopes with mass numbers 56 and 57 offered a unique probe of the physical conditions in the innermost layers of the supernova, where those isotopes are synthesized (Clayton et al. 1992). On the other hand, the COMPTEL instrument mapped the Milky Way in the light of the 1.8 MeV line and found irregular emission along the plane of the Milky Way and prominent “hot-spots” in directions tangent to the spiral arms (Diehl et al. 1995); that map implies that massive stars (SNI and/or WR) are at the origin of galactic $^{26}$Al (as suggested by Prantzos 1991, 1993) and not an old stellar population like novae or AGB stars. Furthermore, COMPTEL detected the 1.16 MeV line of radioactive $^{44}$Ti in the Cas-A supernova remnant (Iyudin et al 1994); that discovery offered another valuable estimate of the yield of a radioactive isotope produced in a massive star explosion (although, in that case the progenitor star mass is not known, contrary to the case of SN1987A).

After that short historical introduction to the field of $\gamma$-ray line astronomy, we turn in the next section into a discussion of the theoretically predicted yields of radioactivities from massive stars, the associated uncertainties and the relevant observational constraints.

3 Stellar Radioactivities: Yields, constraints, detectability

3.1 Overview

All nuclei (except for the primordial isotopes of H and He and those of Li, Be and B) are thermonuclearly synthesized in the hot and dense stellar interiors, which are opaque to $\gamma$-rays. Released $\gamma$-ray photons interact with the surrounding material and are Compton-scattered down to X-ray energies, until they are photoelectrically absorbed and their energy is emitted at longer wavelengths. To become detectable, radioactive nuclei have to be brought to the surface (through vigorous convection) and/or ejected in the interstellar medium, either through stellar winds (AGB and WR stars) or an explosion (novae or supernovae). Their detection provides then unique information on their production sites.

The intensity of the escaping $\gamma$-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, as well as on other features of the production sites (extent of convection, mass loss, hydrodynamic instabilities, position of the “mass-cut” in SNI, etc.). The shape of the $\gamma$-ray lines reflects the velocity distribution of the ejecta, modified by the opacity along the line of sight and can give information on the structure of the ejecta (see e.g. Burrows 1991 for the potential of $\gamma$-ray lines as a tool of supernova diagnostics). Up to now, only the 0.847 MeV $^{56}$Co line from SN1987A and the 1.8 MeV $^{26}$Al line from the inner Galaxy have been resolved (both with the same instrument, the balloon borne GRIS spectrometer), but their “message” is not quite understood yet.
Table 1: Important stellar radioactivities for gamma-ray line astronomy

| DECAY CHAIN | MEAN LIFE* (yr) | LINE ENERGIES (MeV) | SITE | NUCLEAR PROCESS |
|-------------|----------------|---------------------|------|-----------------|
| \(^{7}\text{Be} \rightarrow \(^{7}\text{Li}\) | 0.21 | 0.478 (0.1) | Novae | Expl.H |
| \(^{56}\text{Ni} \rightarrow \(^{56}\text{Co} \rightarrow \(^{56}\text{Fe}\) | 0.31 | \textbf{0.847} (1.) | \textbf{1.238} (0.68) | SN | NSE |
| & | 2.598 (0.17) | 1.771 (0.15) | \(\text{[SN1987A]}\) | \(\text{[SN1991T]}\) |
| \(^{57}\text{Co} \rightarrow \(^{57}\text{Fe}\) | 1.1 | \textbf{0.122} (0.86) | \textbf{0.136} (0.11) | SN | NSE |
| & | \(\text{[SN1987A]}\) | |
| \(^{22}\text{Na}^+ \rightarrow \(^{22}\text{Ne}\) | 3.8 | 1.275 (1.) | Novae | Expl.H |
| \(^{44}\text{Ti} \rightarrow \(^{44}\text{Sc}^+ \rightarrow \(^{44}\text{Ca}\) | 89 | \textbf{1.157} (1.) | \textbf{0.068} (0.95) | SN | \(\alpha\)-NSE |
| & | 0.078 (0.96) | \(\text{[CasA]}\) | | |
| \(^{26}\text{Al}^+ \rightarrow \(^{26}\text{Mg}\) | 1.1 \(\times 10^6\) | \textbf{1.809} (1.) | WR. AGB | St. H |
| & | \(\text{Novae}\) | \(\text{SNII}\) | \(\text{St. Ne}\) | | | | \(\text{[Galaxy]}\) | \(\text{[Vela]}\) | \(\nu\) |
| \(^{60}\text{Fe} \rightarrow \(^{60}\text{Co} \rightarrow \(^{60}\text{Ni}\) | 2.2 \(\times 10^6\) | \textbf{1.332} (1.) | \textbf{1.173} (1.) | SN | n-capt |

* : positron emitters (associated 511 keV line)

* : Double decay chains: the longest lifetime is given; \textbf{Underlined} : lines detected

In \textit{parentheses} : branching ratios; In \textit{brackets} : sites of lines detected

\(St.\ (\text{Expl.})\) : Hydrostatic(Explosive) burning; \(\text{NSE}\) : Nuclear statistical equilibrium

\(\alpha\) : \(\alpha\)-rich "freeze-out"; \(n\text{-capt}\) : neutron captures; \(\nu\) : neutrino-process

Obviously, radionuclides of interest for \(\gamma\)-ray line astronomy are those with high enough yields and short enough lifetimes for the emerging \(\gamma\)-ray lines to be detectable. On the basis of those criteria, Table 1 gives the most important radionuclides (or radioactive chains) for \(\gamma\)-ray line astronomy, along with the corresponding lifetimes, line energies and branching ratios, production sites and nucleosynthetic processes.

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 emission along the Galaxy is expected from the cumulated emission of hundreds or thousands of sources. Characteristic timescales between two explosions are \(\sim 1-2\) weeks for novae (from their estimated Galactic frequency of \(\sim 30\) yr\(^{-1}\), Della Vale and Livio 1995), \(\sim 50-100\) yr for SNII+SNIb and \(\sim 200-400\) yr for SNIa (from the corresponding Galactic frequencies of \(\sim 2\) SNII+SNIb century\(^{-1}\) and \(\sim 0.25-0.5\) SNIa century\(^{-1}\), Tammann et al. 1994, Cappellaro et al. 1997). Comparing those timescales to the decay lifetimes of Table 1 one sees that in the case of the long-lived \(^{26}\text{Al}\) and \(^{60}\text{Fe}\) a diffuse emission is expected; the spatial profile of that emission should reflect the Galactic distribution of the underlying sources. All the other radioactivities of Table 1 should be seen as point sources in the Galaxy except, perhaps, \(^{22}\text{Na}\) from Galactic novae; indeed, the most prolific \(^{22}\text{Na}\) producers, O-Ne-Mg rich novae, have a frequency \(\sim 1/3\) of the total (i.e. \(\sim 10\) yr\(^{-1}\)), resulting in \(\sim 40\) sources active in the Galaxy during the 3.8 yr lifetime of \(^{22}\text{Na}\).

\(^{*}\)The 511 keV line of \(e^+e^-\) annihilation is, in fact, the first \(\gamma\)-ray line ever detected (Johnson et al. 1972), although its origin (probably related to the radionuclides of Table 1) and spatial distribution in the Galaxy are not well understood yet (see Kinzer et al. 2001, and references therein).
3.2 Yields

Yields of radioactive isotopes produced in SNII are displayed in Fig. 1. On the left part of the diagram, Clayton’s (1982) “educated guess” of those yields is presented for illustration purposes; as discussed in Sec. 2, it is in excellent agreement with modern yield calculations.

In Fig. 1 it appears that the stellar mass does not affect substantially those yields; at least in the 15-25 M⊙ mass range, yields do not vary by more than a factor of ∼2-3 (notice, however, that they do not always behave monotonically with mass). Unfortunately, the uncertainties in those yields are difficult to quantify at present, because of the many factors involved: nuclear physics (for instance, the 12C(α, γ) rate or n-capture and n-production cross sections), convection and mass loss prescriptions, position of the mass-cut, neutrino spectra (for some nuclei that may receive contribution from neutrino-induced nucleosynthesis) etc. Taking all those uncertainties into account, it is safe to assume that theoretical yields at present are uncertain by at least a factor of 2 (and, quite probably, by much larger factors). In particular, the yield of all Fe-peak radioactivities (including 44Ti) are quite sensitive to the position of the mass-cut; some discussion on relevant constraints is given in Sec. 3.3. Here we proceed to a comparison between results of 2 recent calculations, by Rauscher et al. (2002 or RHHW2002) and Chieffi and Limongi (2002 or CL2002), performed with state-of-the-art stellar evolution models (including mass loss and a simulation of the explosion) and extended nuclear reaction networks with updated physics. These results illustrate well current uncertainties for 26Al and 60Fe, two radioactivities produced outside the stellar Fe-core.

- In the case of 26Al, the overall agreement is rather good: the RHHW2002 yields are larger by a factor of 2.5 on average than those of CL2002, the difference been more pronounced in the
15 M\(_\odot\) star than in the 25 M\(_\odot\) case. The two calculations converge in the more massive stars, where \(^{26}\text{Al}\) production is dominated by pre-explosive nucleosynthesis in the Ne and H shells. In lower mass stars \(^{26}\text{Al}\) production is dominated by explosive Ne-burning; several factors may then explain the differences between the two calculations: the detailed pre-supernova structure through which the shock-wave runs; the amount of seed nuclei (\(^{23}\text{Na}, \, ^{25}\text{Mg}\) etc) which are products of C-burning and depend thereon on the carbon abundance left off from He-burning, that is on the \(^{12}\text{C}(\alpha, \gamma)\) reaction rate; the \(\nu\)-induced nucleosynthesis (included in RHHW2002 but not in CL2002), etc.

- In the case of \(^{60}\text{Fe}\) the situation is not as satisfactory as for \(^{26}\text{Al}\). \(^{60}\text{Fe}\) is mainly produced by explosive Ne-burning, through neutron captures on stable \(^{56}\text{Fe}\) and \(^{58}\text{Fe}\); its yield depends on the available amount of \(^{22}\text{Ne}\), which releases those neutrons through \(^{22}\text{Ne}(\alpha,\text{n})\), as well as on available \(^{58}\text{Fe}\). There is a factor of \(~\times 10\) difference between the two calculations, for both the 15 M\(_\odot\) and the 25 M\(_\odot\) stars. An explanation of such a large difference appears difficult, especially when the non-monotonic behaviour of the RHHW2002 yields of \(^{60}\text{Fe}\) with stellar mass is taken into account: according to RHHW2002, the \(~\times 20\) M\(_\odot\) region marks the transition from exoergic convective carbon burning (for M\(<\times 20\) M\(_\odot\)) to stars where energy production from central C-burning just compensates for neutrino losses (M\(>\times 20\) M\(_\odot\)); the effect of that transition on the \(^{60}\text{Fe}\) yields has not been investigated yet. Notice that the \(^{60}\text{Fe}\) yields of RHHW2002 are much larger than those of the previous calculations of that same group (Woosley and Weaver 1995). Notice also that the \(^{60}\text{Fe}\) yields of RHHW2002 are larger than the corresponding ones of \(^{26}\text{Al}\), a situation that is not encountered either in CL2002 or in Woosley and Weaver (1995).

### 3.3 Constraints

The issue of the \(^{60}\text{Fe}\) and \(^{26}\text{Al}\) yields in massive stars is of importance, in view of current observational constraints and forthcoming INTEGRAL measurements (see Sec. 4.2). Fig. 1 displays some other observational constraints on SNII radioactivities, obtained for SN1987A (parallelograms for \(^{56}\text{Ni}, \, ^{57}\text{Co}\) and \(^{44}\text{Ti}\), for a 18-20 M\(_\odot\) star) and for other supernovae (on the right of the figure; the corresponding stellar mass is irrelevant in the latter case).

In the case of SN1987A, the \(^{56}\text{Ni}\) yield (0.07 M\(_\odot\)) is obtained through extrapolation of the supernova lightcurve, assumed to be powered by \(^{56}\text{Co}\) decay, to the day of the explosion (e.g. Arnett et al. 1989). The yield of \(^{57}\text{Co}\) is obtained in three different ways: a) through the measured intensity of the 0.122 Mev line of \(^{57}\text{Co}\) and assuming a low optical depth for those photons; b) through the study of the late bolometric lightcurve of SN1987A and assuming that it is dominated by \(^{57}\text{Co}\) decay at days 1100-2000 (this analysis is far less straightforward than in the case of \(^{56}\text{Ni}\)); c) through an analysis of the infrared emission lines of the ejecta. All those methods converge to a value of \(^{57}\text{Co}\) mass of \(~3 \times 10^{-3}\) M\(_\odot\) (see Fransson and Kozma 2002). Finally, the yield of \(^{44}\text{Ti}\) is evaluated through methods (b) and (c), albeit with substantial difficulties, due to the complex physics of supernova heating and cooling involved and the role of positrons; current estimates give values in the 0.5-2 \(\times 10^{-4}\) M\(_\odot\) range (Fransson and Kozma 2002), while Sollerman (2002) suggests an upper limit of 1.1 \(\times 10^{-4}\) M\(_\odot\).

These observational constraints compare rather well with theoretical predictions for 18-20 M\(_\odot\) stars (the estimated progenitor mass of SN1987A, on the basis of its optical luminosity, e.g. Arnett et al. (1989)). Notice, however, that model results in Fig. 1 correspond to stars calculated with initial metallicity Z=Z\(_\odot\), while the progenitor of SN1987A presumably had LMC metallicity, namely Z\(~\sim 0.3\) Z\(_\odot\). Notice also that Thielemann et al. (1996) obtain a larger \(^{44}\text{Ti}\) yield for the 20 M\(_\odot\) star (1.7 \(\times 10^{-4}\) M\(_\odot\)), due to a difference in the way of simulating the explosion: the “thermal bomb” they use leads to a larger entropy and more important \(\alpha\)-rich freeze-out than in the case of the piston-driven explosion adopted by RHHW2002. Such a high \(^{44}\text{Ti}\) yield is marginally detectable by INTEGRAL (see next section).
Data on the right of Fig. 1 concern $^{56}$Ni yield estimates for extragalactic SNII. Based on a sample of 8 SNIIP (the “standard” SNII, with a “plateau” in the optical lightcurve) and assuming a bolometric correction similar to the one of SN1987A, Sollerman (2002) finds a mean value of 0.075 M$_\odot$ with a standard deviation of 0.03 M$_\odot$. He notices, however, that SNII with much lower and higher yields than the “canonical” one have also been found. In the former case belong SN1994W: the extremely rapid fading of its light curve suggests a $^{56}$Ni yield lower than 0.015 M$_\odot$. On the other hand, SN1998bw is the most $^{56}$Ni-rich supernova today: detailed modelling of its late emission requires $^{56}$Ni yields of 0.5-0.9 M$_\odot$, and simple arguments lead to a lower limit of 0.3 M$_\odot$ (Sollerman et al. 2002). Thus, it appears that the $^{56}$Fe yield of massive stars is far from being a “universal constant” of $\sim$0.075 M$_\odot$, a fact that may have interesting implications for stellar models as well as galactic chemical evolution, especially concerning the observed scatter of abundance ratios in halo stars (Ishimaru et al. 2002).

Finally, the $^{44}$Ti yield of CasA is inferred from the 1.16 MeV line flux of $^{44}$Sc decay detected by COMPTEL ($3.3\pm0.6 \times 10^{-5}$ cm$^{-2}$ s$^{-1}$) and the CasA distance (3.4 kpc) and age (320 yr) and amounts to $\sim$1.7 $10^{-4}$ M$_\odot$ (Iyudin et al. 1999). An independent evaluation of the $^{44}$Ti yield in CasA came recently, through detection of the low energy decay lines of $^{44}$Ti by BeppoSAX: the detected flux at 68 and 78 keV implies a $^{44}$Ti mass of 1-2 $10^{-4}$ M$_\odot$, depending on the modelisation of the underlying continuum spectrum (Vink et al. 2001; Vink and Laming this volume). These yields are larger than the average $^{44}$Ti yields of RHHW2002 (see Fig. 1), typically by a factor of $\sim$3, but compatible with those of Thielemann et al. (1996). Notice, however, that these estimates suffer from uncertainties related to the ionisation state of the SN remnant; an ionised medium could slow down the electron-capture decay of that radionuclide and explain the observed flux with a smaller yield (see Mochizuki et al. 1999).

3.4 Detectability

For tutorial purposes, we present in Fig. 2 a schematic view of the $\gamma$-ray line emissivity of a “typical” SNII, over three different timescales: 10 years, 10 centuries and a few Myrs. The figure is based on the yields of Fig. 1 and is calculated by assuming a SN1987A-like opacity for the ejecta.

Notice that, if the RHHW2002 yields of $^{60}$Co are correct, the $^{60}$Co lines might dominate the $\gamma$-ray line emission of the SN for a couple of years, between 5 and 8 years after the explosion; that possibility was suggested by Clayton (1982) for very young SN remnants in the Milky Way. Unfortunately, the expected flux from SN1987A was below the sensitivity limits of instruments aboard CGRO and it will also be below the detection threshold of INTEGRAL (which is launched $\sim$15 years after the explosion, while $^{60}$Co has a mean life of 7.6 yr). The role of $^{60}$Co for the late lightcurve of SN1987A was studied in Timmes et al. (1996). It may well be that the current difficulties in modelling the late bolometric lightcurve of that supernova and its infrared line emissivity (see previous section) may be, at least partially, due to an inadequate account of the energy input from that isotope.

The expected 1.16 MeV $\gamma$-ray line flux from $^{44}$Ti in SN1987A ($\sim10^{-5}$ cm$^{-2}$ s$^{-1}$) lies at the detection limit of INTEGRAL and will be one of the prime targets of the SPI instrument aboard that satellite. Even a 3-$\sigma$ upper limit would bring important information on the position of the mass-cut and the explosion mechanism of that supernova, since $^{44}$Ti yield is more sensitive to the mass-cut than other isotopes (e.g. Timmes et al. 1996). On the other hand, Fig. 2 reveals also that $^{44}$Ti from centuries-old SN remnants in the Milky Way should be detectable by INTEGRAL; here again, a positive detection will reveal hitherto unknown Galactic SN remnants, while a negative result is expected to place interesting constraints on the frequency of the production sites of that isotope and on the corresponding yields. Indeed, on the basis of Woosley and Weaver (1995) yields Timmes et al. (1996) estimate that, in order to explain the solar abundance of $^{44}$Ca,
Figure 2: Schematic evolution of the gamma-ray line emissivity of a “typical” SNII, over three different timescales (10 years, 10 centuries, few Myrs). The figure is based on the yields of Fig. 1 and on an opacity for the SN ejecta similar to the one in the case of SN1987A. On the right are shown maximum detection distances for INTEGRAL, corresponding to those emissivities; INTEGRAL may detect Ti44 up to 50 kpc (e.g. from SN1987A) or Al26 from a nearby event, closer than 0.3 kpc (e.g. from objects in the Vela region, see text).

One has to invoke either a higher SN frequency in the Galaxy or high $^{44}$Ti yields or production of $^{44}$Ca in rare events, like sub-Chandrasekhar mass SNIa. An analysis of COMPTEL map of the inner Galaxy in the light of 1.16 MeV suggests that the first two possibilities should be excluded, otherwise more and/or brighter “hot-spots” than actually observed should be found by COMPTEL (The et al. 2000). In that respect, it is interesting to notice that tantalizing hints for $^{44}$Ti emission from the nearby source GRO J0852-4642, a previously unknown supernova remnant, were recently reported (Iyudin et al. 1998, Aschenbach et al. 1999; but, see also Schönfelder et al. 2000).

Long-lived radioactivities are difficult to detect from individual sources, even with next generation instruments. For instance, in the case of $^{26}$Al, an exceptionally close site (closer than $\sim$0.3 kpc) is required for its 1.8 MeV line to be detectable by INTEGRAL; the Vela region might offer just such a chance, in view of some intriguing hints from COMPTEL observations (see Sec. 4.4). In the following we shall focus on the long-lived radioactivities $^{26}$Al and $^{60}$Fe. During their $\sim$Myr lifetimes the collective emission from tens of thousands of sources gives rise to a diffuse emission along the plane of the Milky Way; only the $^{26}$Al emission has been detected up to now.

4 Diffuse $\gamma$-ray line emission from long-lived $^{26}$Al and $^{60}$Fe in the Milky Way

4.1 Overview

COMPTEL is the only instrument with imaging capabilities that detected the Galactic 1.8 MeV line emission (Fig. 3). The data shows clearly a diffuse, irregular, emission along the Galactic plane, allowing to eliminate: i) a unique point source in the Galactic centre and/or a nearby local bubble in that direction; ii) an important 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 (like nova or low mass AGB stars), since a smooth flux distribution is expected.
Figure 3: Sky map in the light of the 1.8 MeV line of Al26, according to the analysis of the 5-year COMPTEL data by Oberlack (1997); several “hot-spots” in the inner Galaxy and along the line of sight to spiral arms (Cygnus, Carina) are clearly identified.

in that case (Diehl et al. 1995). Identification of some of the observed features (“hot-spots”) with tangents to spiral arms seems quite plausible and suggests that massive stars are at the origin of $^{26}$Al (Prantzos and Diehl 1996).

Estimates of the galactic mass of $^{26}$Al rely on assumptions about the spatial distribution of the underlying sources. All plausible disk models tested by the COMPTEL team yield a mass of $\sim 2 M_\odot$. Introducing a spiral structure to the axisymmetric disk models improves the fit to the data and implies that between 60 and 100 % of the $^{26}$Al may lie on the spiral arms (Diehl et al. 1998). It should be noticed that the derived spatial distribution of $^{26}$Al depends on the method of analysis. As shown by Knödlseder et al. (1999) some imaging analysis methods lead to all-sky maps with more pronounced localised features than some others; still, the irregular nature of the 1.8 MeV emission along the Galactic plane and the localised “hot-spots” are revealed by all imaging methods, in a statistically significant way (Plüschke et al. 2001a).

4.2 Sources of $^{26}$Al and the role of $^{60}$Fe

The $^{26}$Al yields presented in Fig. 1 concern massive stars exploding as SNII. Even more massive stars (>30 $M_\odot$) may produce substantial amounts of $^{26}$Al during central (hydrostatic) H-burning and eject them through their powerful stellar winds, in the WR stage (Prantzos and Cassé 1986); the WR yields are relatively well determined (e.g. Meynet et al. 1997), but the explosive yields of those stars (which ultimately explode as SNIb) are very poorly known at present.

Under the most favorable conditions (highest possible yields for SNII allowed by current uncertainties; accounting for the strong metallicity dependence of WR yields, which favours sources in the inner Galaxy; adopting a mildly steep IMF, i.e. with the Salpeter slope of -1.35 instead of the Scalo slope of -1.7), it turns out that both SNII and WR can account for $\sim 2 M_\odot$/Myr of $^{26}$Al (e.g. Prantzos and Diehl 1996). It may well be that both classes of sources contribute equally to the Galactic $^{26}$Al (a coincidence not “stranger” than the quasi-equality between the solar abundances of s- and r- elements, or between the contributions of the dark matter and dark energy to the density of the Universe). However, it is interesting to see whether independent constraints can be used to distinguish between the SNII and WR contributions and identify a dominant component (assuming that there is one).
One such constraint is the flux ratio of the $\gamma$-ray lines of $^{60}$Fe (1.17 and 1.33 MeV) and $^{26}$Al (1.8 MeV). Indeed, $^{60}$Fe is predicted to be co-produced with $^{26}$Al in SNII (in almost the same zones and in similar amounts, Fig. 1), but not in WR stars. If SNII dominate galactic $^{26}$Al production, an important $^{60}$Fe emission is then expected (flux ratio: $\frac{^{60}Fe}{^{26}Al} = \frac{Y_{^{60}Fe}}{Y_{^{26}Al}/\tau_{^{26}Al}}$, where $Y$ represent yields averaged over the IMF and $\tau$ the corresponding decay lifetimes); if WR stars are dominant, the $\gamma$-ray line flux ratio of $^{60}$Fe/$^{26}$Al is expected to be extremely low.

The $\frac{^{60}Fe}{^{26}Al}$ ratio of SNII depends on stellar models (and slightly on the IMF). The Woosley and Weaver (1995) yields lead to a flux ratio of 0.16 (Timmes et al. 1995), and so do the recent ones of CL2002 (note that the absolute $^{60}$Fe and $^{26}$Al yields of CL2002 are $\sim$ 4 times lower than those of WW1995); however, the most recent results of the Santa Cruz group (RHHW2002) lead to a surprisingly large flux ratio $\frac{^{60}Fe}{^{26}Al} \sim$0.4. On the other hand, current observational upper limits, obtained by GRIS (Naya et al. 1998) and COMPTEL (Diehl 2000) are close to 0.15. It appears then that: a) the RHHW2002 yields can produce $\sim$1 M$_\odot$ of Galactic $^{26}$Al, but should be excluded by the non-detection of $^{60}$Fe; b) the CL2002 yields produce a Galactic $^{26}$Al mass of $\sim$0.4 M$_\odot$, too low to explain the detected 1.8 MeV flux. Taken at face value, the most recent SNII yields apparently exclude SNII as dominant sources of Galactic $^{26}$Al. Does this mean that WR stars constitute a viable alternative?

WR stars can indeed provide $\sim$2 M$_\odot$/Myr of $^{26}$Al (Meynet et al. 1997), provided that the strong metallicity dependence of the yields is taken into account. Moreover, Knödlseder (1999) showed that a map of the ionising 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. Finally, Knödlseder et al. (2001) point out that one of the prominent “hot-spots” in the COMPTEL 1.8 MeV sky-map, the Cygnus region, is an association of massive stars with no sign of recent supernova activity. All these observational and theoretical indices favour WR stars as dominant $^{26}$Al contributors. However, in that case, the 1.8 MeV longitude profile (or, equivalently, the $^{26}$Al radial profile) should be steeper than observed (see Fig. 5).

In summary, there is no satisfactory explanation at present for the flux of the 1.8 MeV line and its spatial distribution in the Milky Way. INTEGRAL is expected to provide a more detailed spatial profile than COMPTEL and to put more stringent limits (or, perhaps, to detect) emission from $^{60}$Fe. Only when the nature of the major $^{26}$Al sources is clarified it will become possible to tackle the question of their Galactic distribution (i.e. with any yield dependence on metallicity - or other factors - properly taken into account).

4.3 The $^{26}$Al line width: a hint for mixing of SN ejecta in the ISM?

The width of the $^{26}$Al line was already discussed by Ramaty and Lingenfelter (1977) who pointed out that $^{26}$Al ejected from SN should decelerate in the ISM in a timescale short compared with its decay timescale; as a consequence, the emitted $\gamma$-ray line should be quite narrow (narrower than the $\sim$2 keV width imposed by Galactic rotation), making its detection relatively easy.

The HEAO-3 Ge detectors found the line to be narrow indeed: FWHM<3 keV (Mahoney et al. 1984); however, the GRIS instrument measured a FWHM=5.4±1.4 keV, $\sim$3 times larger
than HEAO-3 and much larger than allowed by Galactic rotation (Naya et al. 1996). If real, that large width can be interpreted either as kinematic (with the bulk of $^{26}$Al moving with velocities $\sim 540$ km/s) or thermal (with most $^{26}$Al atoms brought to temperatures $T \sim 4.5 \times 10^8$ K). The thermal origin seems improbable, since it would imply that all $^{26}$Al is produced in $\sim 200$ mini-starburst regions in the inner Galaxy regions (Chen et al. 1997). A non-thermal origin could be understood if $^{26}$Al nuclei are incorporated in dust grains, which are launched by the SN explosion (Chen et al. 1997), or accelerated by the SN shock wave (Ellison et al. 1997) or repeatedly accelerated by SN shocks (Sturner and Naya 1999).

The SPI instrument of INTEGRAL will clarify that issue, by measuring the line width and also the latitude distribution of the line emission. Already, COMPTEL measurements imply a vertical scaleheight of $< 220$ pc for the $^{26}$Al distribution and suggest that the velocity of the bulk of $^{26}$Al has not as large a component perpendicularly to the Galactic plane as suggested by the kinematic interpretation of the GRIS measurements (Oberlack 1997).

4.4 $^{26}$Al “hot-spots”: monitoring stars, superbubbles and young stellar associations

The study of individual “hot-spots” revealed by COMPTEL bears on our understanding of the evolution of young stellar associations (in the cases of Cygnus, Carina and Centaurus-Circinus) and even individual stars (in the case of Vela).

The Cygnus regions was studied with population synthesis models by two groups (Cervinho et al. 2001, Plüschke et al. 2001b). The resulting morphology of the 1.8 MeV emission compares well with the COMPTEL data. However, in the case of Carina, the predicted absolute flux is smaller (by a factor of 5-20) than detected by COMPTEL (Knödlseder et al. 2001). That discrepancy may imply something interesting, either for the (in)completeness of the stellar census of that association or for the $^{26}$Al yields. INTEGRAL will establish more accurately the morphology of those “hot-spots” and further test the “massive star group” origin of $^{26}$Al.

Another target of importance for future 1.8 MeV studies is the Orion/Eridanus region. COMPTEL surveys of the anticenter region show significant ($5 \sigma$) extended emission towards the south of the Orion molecular clouds. That emission could be attributed (Diehl 2002) to $^{26}$Al ejected by the prominent Orion OB1 association and expanded into the low density cavity of the Eridanus bubble. The expansion of supernova ejected into a previously formed cavity of peculiar shape (and not into a medium with radial symmetry) is a novel and interesting field of study, opened by COMPTEL and left for INTEGRAL to explore.

Finally, the Vela region offers the opportunity to measure (or put upper limits on) $^{26}$Al yields from individual sources. The morphology of the rather extended 1.8 MeV emission detected by COMPTEL does not allow identification with any of the three known objects in the field (the Vela SNR, the closest WR star $\gamma^2$ Vel and SNR RX-J0852-4622); all three objects lie closer than 260 pc, according to recent estimates. COMPTEL measurements are compatible with current yields of SNII (in the case of Vela SNR) and marginally compatible with current yields of $\gamma^2$ Vel (Oberlack et al. 2000). INTEGRAL measurements in the Vela region are then expected to place more stringent constraints on stellar models.

5 Summary

The aim of Gamma-Ray Astronomy with Radioactivities, as explicitly defined by the “founding fathers” of the field in the 60ies (see Sec. 2) was to probe stellar nucleosynthesis as well as supernova structure and energetics. This original aim was reached in a spectacular way in the case of SN1987A (which, however, remains today - and, probably, for sometime in the future - a unique object in that respect).

On the other hand, the legacy of HEAO-3 and COMPTEL set new aims to the field of
**Gamma-Ray Astronomy with long-lived Radioactivities:** to probe the large-scale distribution of active nucleosynthesis sites in the Galaxy and the properties/history of any clusterings in that distribution (young stellar associations, individual objects). *INTEGRAL* is expected to perform this next step.

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