ASTROPHYSICAL $\gamma$-RAY LINES: A PROBE OF STELLAR NUCLEOSYNTHESIS AND STAR FORMATION

Nikos Prantzos
Institut d’Astrophysique de Paris, France

ABSTRACT

Astrophysical gamma-ray spectroscopy is a most valuable tool for studying nuclear astrophysics, as well as recent star formation in the Milky Way. After a short, historical, introduction to the field, I present a brief review of the most important current issues. Emphasis is given to radioactivities produced by massive stars and associated supernova explosions, and in particular, those related to observations presently carried out by INTEGRAL: short-lived $^{44}$Ti from CasA and SN1987A and long-lived $^{26}$Al and $^{60}$Fe from massive stars; various candidate sources of positrons for the 511 keV emission of the Galactic bulge are also critically discussed.

Key words: Nucleosynthesis, supernovae, radioactivities, Milky Way, gamma-ray lines.

1. HISTORICAL OVERVIEW

The starting point of $\gamma$-ray line astronomy with cosmic radioactivities is usually considered to be the landmark paper of Clayton, Colgate and Fishman (1969). That work clarified the implications of the production of $^{56}$Ni (a doubly magic, and yet unstable nucleus) during explosive Si-burning in supernovae (SN). In particular, it opened exciting perspectives for $\gamma$-ray line astronomy, by suggesting that any supernova within the local group of galaxies would be detectable in the characteristic $\gamma$-ray lines resulting from the radioactive decay of $^{56}$Ni and its daughter nucleus $^{56}$Co.

In the 70’s D. Clayton identified most of the radioactivities 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 SN 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 $^{26}$Al escaped Clayton’s (1982) attention, perhaps because its daughter nucleus $^{26}$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 $^{26}$Mg is produced as $^{26}$Al, the resulting Galactic flux from tens of thousands of supernovae (during the $\sim$1 Myr lifetime of $^{26}$Al) would be of the order of $10^{-4}$ cm$^{-2}$ s$^{-1}$.

In the case of $^{26}$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 $^{26}$Al ($\sim$ 2 M$_{\odot}$ per Myr, assuming steady state) was difficult to accommodate in conventional models of galactic chemical evolution if SN were the main $^{26}$Al source (Clayton 1984), since $^{27}$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 $^{56}$Co $\gamma$-ray lines were detected 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 SNII (exploding 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 massive exploding stars ($\sim$10 M$_{\odot}$) allows only small amounts of $\gamma$-rays to leak out of SNII, making the detectability of such objects problematic. 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 radioactive chain $^{56}$Ni$\rightarrow^{56}$Co$\rightarrow^{56}$Fe; this confirmed a 20-year old con-
Figure 1. Yields of radioactive nuclei from massive exploding stars. On the left, Clayton’s (1982) predictions for average SN yields are given (based on the assumption that the corresponding stable daughter isotopes are produced in their solar abundances as radioactive progenitors); the uncertainty in $^{60}$Fe yield stems from the unknown percentage of its contribution to the production of stable $^{60}$Ni (which may also be produced as unstable $^{60}$Co; the limits of the error bar correspond to 0 percent and to 100 percent contribution, respectively). In the middle, recent theoretical results are plotted as a function of stellar mass (filled symbols, from Rauscher et al. 2002), while open parallelograms indicate observational constraints from SN1987A, a 18-20 $M_{\odot}$ star. On the right appear other observational constraints, either from CasA (for $^{44}$Ti) or from extragalactic SN (for $^{56}$Ni, see also Fig. 3).

jecture, 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 contributions 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 approximately tangent to the spiral arms (Diehl et al. 1995); that map implies that massive stars (SNII 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). On the other hand, it also created some new problems, since current 1D models of core collapse supernova do not seem able to account for the yield inferred from the observations; however, recent axisymmetric models of rotating star explosions offer interesting perspectives in that respect (see next section).

Finally, after CGRO and before INTEGRAL, another important discovery was made in the field: the RHESSI experiment confirmed the detection of $^{26}$Al in the Galaxy, but it also detected the characteristic decay lines of $^{60}$Fe, another long-lived isotope with $\sim$2 Myr period (Smith 2004, and this volume). The detected $^{60}$Fe emissivity is, however, considerably lower than expected from current models of nucleosynthesis in core collapse SN. The implications of that discovery are studied in Prantzos (2004) and in Sec. 4.

Table 1 summarizes our current picture of stellar radioactivities and associated $\gamma$-ray lines. In the following we shall focus on the radioactivities produced by massive stars and associated supernova explosions, and in particular, those related to observations presently carried out by INTEGRAL. Similar reviews have been presented by Diehl and Timmes (1998) and Knödlseder and Vedrenne (2001). The current status of the physics of supernova explosions is reviewed by Hillebrandt (this volume).
Table 1. Important stellar radioactivities for gamma-ray line astronomy

| DECAY CHAIN | MEAN LIFE \(^{\text{yr}}\) | LINE ENERGIES (MeV) | SITE [Detected] | 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 | 0.847 (1) | SN [SN1987A] | NSE |
| | | 2.598 (0.17) | | |
| | | 1.771 (0.15) | | |
| \(^{57}\text{Co} \rightarrow^{57}\text{Fe}\) | 1.1 | 0.122 (0.86) | SN [SN1987A] | NSE |
| | | 0.136 (0.11) | | |
| \(^{22}\text{Na} \rightarrow^{22}\text{Ne}\) | 3.8 | 1.275 (1) | Novae | Expl.H |
| \(^{44}\text{Ti} \rightarrow^{44}\text{Sc} \rightarrow^{44}\text{Ca}\) | 89 | 1.157 (1) | SN [CasA] | \(\alpha\)-NSE |
| | | 0.068 (0.95) | | |
| | | 0.078 (0.96) | | |
| \(^{26}\text{Al} \rightarrow^{26}\text{Mg}\) | 1.1 \(10^{6}\) | 1.809 (1) | WR, AGB St.H Novae Expl.H SNII St.Ne, Expl.Ne, \(\nu\) [Galaxy, Vela] |
| \(^{60}\text{Fe} \rightarrow^{60}\text{Co} \rightarrow^{60}\text{Ni}\) | 2.2 \(10^{6}\) | 1.332 (1) | SN [Galaxy] | n-capt |
| | | 1.173 (1) | | |

\(\alpha\): positron emitters (associated 511 keV line)  
* : Double decay chains; the longest lifetime is given; Underlined: lines detected  
In parentheses: branching ratios; In brackets: sites of lines detected  
St. (Expl.): Hydrostatic (Explosive) burning; NSE: Nuclear statistical equilibrium  
\(\alpha\): \(\alpha\)-rich "freeze-out"; n-capt: neutron captures; \(\nu\): neutrino-process

2. \(^{56}\text{Ni}\) AND \(^{44}\text{Ti}\) FROM CORE COLLAPSE SUPERNOVAE

Both \(^{56}\text{Ni}\) and \(^{44}\text{Ti}\) are produced in the innermost layers of core collapse SN, through explosive Si-burning. In the high temperatures resulting from the passage of the shock wave, matter enters Nuclear Statistical Equilibrium (NSE). Electron captures are too slow to change the neutron/proton ratio during the \(\sim\) 1 s timescale of explosive nucleosynthesis and thus most of the original composition (consisting of \(^{28}\text{Si}\), with equal numbers of protons \(Z\) and neutrons \(N\)) turns into \(^{56}\text{Ni}\) (\(Z=N=28\)).

After the passage of the shock wave, material brought to NSE cools down. In environments with relatively low densities this happens in the presence of a large concentration of free \(\alpha\) particles, which have no time to merge back to Fe-peak nuclei through the inefficient 3-\(\alpha\) reaction (the rate of which scales with density squared). This "\(\alpha\)-rich freeze-out" process favours in particular the production of \(^{44}\text{Ti}\) (see discussion in Thielemann et al. 1996, and in particular Figs. 3 and 4a).

The yields of \(^{56}\text{Ni}\), \(^{44}\text{Ti}\) and other Fe-peak nuclei are extremely difficult to evaluate from first principles, at least in the framework of current models of core collapse supernova. The layers undergoing explosive Si-burning are very close to the "mass-cut", that fiducial surface separating the supernova ejecta from the material that falls back to the compact object (after the passage of the reverse shock). Since no consistent model of a core collapse supernova explosion exists up to now (e.g. Janka et al. 2003), the position of the mass-cut is not well constrained. Current 1D simulations suggest that the yield of \(^{44}\text{Ti}\) is even more sensitive to the mass-cut than the one of \(^{56}\text{Ni}\) (see Fig. 2).

The presence of \(^{56}\text{Ni}\) in SN1987A has been unambiguously inferred from the detection of the \(\gamma\)-ray lines of the decay of its daughter nucleus \(^{56}\text{Co}\). The yield of \(^{56}\text{Ni}\) has been estimated from the extrapolation of the early optical lightcurve to the origin of the explosion (precisely known thanks to the neutrino signal, see Arnett et al. 1989 and references therein); the derived value, 0.07 M\(_{\odot}\), is often taken as a "canonical" one for core collapse SN.

It turns out, however, that core collapse SN display a wide range of \(^{56}\text{Ni}\) values, spanning a range of at least one order of magnitude, as can be seen in Fig. 3 (Hamuy 2003 and references therein). Despite the large error bars, it seems that there is a clear cor-
relation between the amount of $^{56}$Ni and the energy of the explosion (obviously, because a shock of larger energy heats a larger amount of material to NSE conditions).

$^{44}$Ti has not been directly detected in SN1987A up to now. Modelling of the late lightcurve of that supernova suggests that it may be powered by 1-2 $10^{-4}$ M$_\odot$ of $^{44}$Ti (Motizuki and Kumagai 2003a) and similar values are obtained through analysis of the infrared emission line of the ejecta (Fransson and Kozma 2002). Note that the evaluation of the $^{44}$Ti yield through these methods suffers from considerable uncertainties, due to the complex physics of the supernova heating and cooling and the role of positrons. The derived amount (and especially the higher value) is rather high compared to the results of 1D models of 18-20 M$_\odot$ stars (e.g. from Rauscher et al. 2002, see Fig. 1). Moreover, the $^{44}$Ti/$^{56}$Ni mass ratio is around 3 times the solar ratio of the corresponding stable isotopes ($^{44}$Ca/$^{56}$Fe)$_\odot$, too high to be explained by current 1D models, as will be discussed below.

Despite these high values, $^{44}$Ti from SN1987A seems beyond the detection capabilities of INTEGRAL, now that the on-flight performance of SPI is well established. The analysis of Motizuki and Kumagai (2003a) indicates that the expected flux in the 1157 keV line is $\sim 5 \times 10^{-6}$ ph/cm$^2$/s, i.e. considerably lower than the $\sim 2 \times 10^{-5}$ ph/cm$^2$/s sensitivity of SPI for an exposure of 1 Ms.

The $\gamma$-ray lines of $^{44}$Ti have been detected in the $\sim 320$ yr old CasA supernova remnant, lying at a distance of $\sim 3.4$ kpc from earth. Both the high energy line at 1.157 MeV and the low energy ones, at 68 and 78 keV, have been detected, respectively by COMPTEL (Iyudin et al. 1994) and Beppo-SAX (Vink et al. 2001). The detected flux of $3.3 \pm 0.6 \times 10^{-5}$ ph/cm$^2$/s from COMPTEL, points to a $^{44}$Ti yield of $\sim 1.7 \times 10^{-4}$ M$_\odot$. Similar values, i.e. 1-2 $10^{-5}$ M$_\odot$, are obtained through a study of the combined fluxes of the low energy lines (Vink and Laming 2002), although the modelisation of the underlying continuum spectrum makes the analysis very difficult.

The $^{44}$Ti yield of CasA is comparable to the one implied by the optical and infrared observations of SN1987A. Note, however, that the CasA yield suffers from uncertainties related to the ionisation stage of the CasA remnant. $^{44}$Ti decays by orbital elec-
According to Motizuki et al. (1999), the amount of remnant, otherwise its abundance should be lower, if its decay (Mochizuki et al. 1999); the derived yield of the corresponding stable isotopes is also displayed as a horizontal shaded band (assuming that its decay rate has not been affected by ionisation in the CasA remnant, otherwise its abundance should be lower, according to Motizuki et al. 1999). The amount of $^{44}$Ti in SN1987A is derived from its late optical lightcurve (Motizuki and Kumagai 2003, see Fig. 4). The diagonal dotted line indicates the solar ratio of the corresponding stable isotopes ($^{44}$Ca/$^{56}$Fe)$_{⊙}$.

The results of those calculations are plotted as $^{44}$Ti yield vs $^{56}$Ni yield in Fig. 5, where the solar ratio of the corresponding stable isotopes is also displayed as a diagonal line. It can be seen that:

- There is broad agreement between LC03 and RHHW02, at least around the value of 0.07-0.1 $M_⊙$ of the $^{56}$Ni yield.
- Except for the lowest $^{56}$Ni yields, $^{44}$Ti and $^{56}$Ni yields of LC03 both increase with the energy of the explosion, at a quasi-constant average ratio of $\sim 3 \times 10^{-4}$.
- This value is $\sim 3$ times lower than the solar ratio of ($^{44}$Ca/$^{56}$Fe)$_{⊙} \sim 10^{-3}$. This implies that such explosions cannot produce the solar $^{44}$Ca, since $^{56}$Fe would be overproduced in that case (e.g. Timmes et al. 1996). Moreover, there is another important source of Fe, SNIa, which produce about 0.5-0.65 of solar $^{56}$Fe, but very little $^{44}$Ca; this makes the deficiency of $^{44}$Ca from core collapse SN even more serious than appearing in Fig. 5, since it implies that core collapse explosions should produce a $^{44}$Ti/$^{56}$Ni ratio at least twice solar in order to compensate for the $^{56}$Fe production of SNIa. Such a high ratio is also what is required to explain the high value of the $^{44}$Ti yield in SN1987A.
- In the case of CasA, one has two choices. The first is a more limited range of stellar masses (from 15 to 25 $M_⊙$), but they considered only a fixed “canonical” value for the kinetic energy of the explosion; their results supersede those of Woosley and Weaver (1995), obtained with the same stellar evolution code but with an older set of nuclear reaction rates. Both calculations of RHHW02 and LC03 are made with the same reaction rate libraries and concern stars of solar initial metallicity. It is questionable to what extent they apply to SN1987A, the progenitor of which presumably had an LMC metallicity of 0.3 $Z_⊙$.

In summary: from optical observations we have a wide range of values for the $^{56}$Ni yields of core collapse SN, and a precise value of 0.07 $M_⊙$ for SN1987A; and for $^{44}$Ti yields we have similar values, i.e. 1-2 $10^{-4}$ $M_⊙$, for both SN1987A (indirectly, through the modelisation of the UVOIR light) and for CasA (directly, through $γ$ ray lines, albeit with a systematic uncertainty resulting from poorly constrained ionisation effects). How do these results compare with theoretical expectations?

The most detailed relevant calculations have been recently performed for 1D models, concerning stars in the 15-35 $M_⊙$ range and parametrised by the energy of the explosion (Limongi and Chieffi 2003, LC03). Also, Rauscher et al. (2002, RHHW02) investigated electron capture and an ionised medium could slow down its decay (Mochizuki et al. 1999); the derived yield could be considerably smaller in that case (Motizuki and Kumagai 2003b). On the other hand, ionisation is expected to play a small role in the aforementioned derivation of the $^{44}$Ti yield in SN1987A, but the remnant of that SN is rapidly evolving (Michael et al. 2002); if $^{44}$Ti enters a high ionisation stage in the near future, the expected $γ$-ray line fluxes from SN1987A should be accordingly reduced (see Motizuki and Kumagai 2003b).

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to assume a very energetic explosion and, according to 1D models, get a $^{44}$Ti yield compatible with CasA observations; but then a high $^{56}$Ni yield of $>0.2\, M_\odot$ is implied by those same models, leading to the question “why such a bright explosion as CasA went undetected back in the 1680s?” (e.g. Hartmann et al. 1996). The second option is to assume that the $^{56}$Ni yield was much smaller than suggested by 1D models producing high $^{44}$Ti (thus explaining why CasA went undetected); in that case it becomes clear that current 1D models are unable to explain the situation in either CasA or SN187A.

A solution to this problem of “missing $^{44}$Ti (and $^{44}$Ca)” is provided by multi-dimensional models of the energetic explosions of rotating massive stars (hypernovae). In such explosions, material falling onto the central remnant forms an accretion disk, and a fraction of that material is ejected in the form of two jets (or a bipolar wind), which interact with the stellar mantle. According to Nagataki et al. (1998), material along the jet axis undergoes higher temperatures and entropies (i.e. lower densities) than material in normal spherical explosions. Such conditions are particularly favourable to an “α-rich freeze-out” and lead to the production of large $^{44}$Ti amounts and $^{44}$Ti/$^{56}$Ni ratios. In Fig. 5 it can be seen that recent nucleosynthesis results obtained in the framework of such models (from Maeda and Nomoto 2003) may cure all the aforementioned problems.

At least in the case of SN1987A, there is convincing evidence that the explosion was axisymmetric and not spherical (see Wang et al. 2002 and references therein). On the other hand, $^{44}$Ti produced in the jets is ejected at much higher velocities than in spherical symmetric explosions, reaching up to 25000 km/s according to Maeda and Nomoto (2003 and Fig. 6). This makes its lines rather broad and their detection by a spectrometer like SPI even more difficult. For that reason, detection of the $^{44}$Ti lines from CasA and measurement of their width is one of the most critical issues in γ-ray line astronomy today, and one of the prime objectives of SPI/INTEGRAL.

Finally, continuing search for $^{44}$Ti lines in the Milky Way could reveal young supernova remnants and put interesting statistical constraints on $^{44}$Ti yields and supernova frequencies. Such a search has been already performed in the past with HEAO-3, SMM and COMPTEL data; a Monte Carlo analysis by The et al. (2000) showed that a rather rare supernova type with high $^{44}$Ti yield is favoured by the absence of a $^{44}$Ti signal from the inner Galaxy. Similar conclusions are reached with preliminary INTEGRAL data (see contribution by Renaud et al. this volume).

3. $^{26}$Al and $^{60}$Fe from Massive Stars

$^{26}$Al is the first radioactive nucleus ever detected in the Galaxy through its characteristic gamma-ray line signature, at 1.8 MeV (Mahoney et al. 1984). Taking into account that its lifetime of ~1 Myr is short w.r.t. galactic evolution timescales, its detection convincingly demonstrates that nucleosynthesis is still active in the Milky Way (Clayton 1984). The detected flux is $\sim 4 \times 10^{-4} \, \text{cm}^{-2} \, \text{s}^{-1}$ and corresponds to $\sim 2 \, M_\odot$ of $^{26}$Al currently present in the ISM (and produced per Myr, assuming a steady state situation).

The COMPTEL instrument aboard CGRO mapped the 1.8 MeV emission in the Milky Way and found it to be irregular, with prominent “hot-spots” probably associated with the spiral arms (Diehl et al. 1995). The spatial distribution of $^{26}$Al suggests that massive stars are at its origin (Prantzos 1991, Prantzos and Diehl 1996), since any population of long-lived objects (AGB stars or novae) is expected to be more smoothly distributed.

The detailed mapping of the Galactic distribution of $^{26}$Al, obtainable through a determination of the distances to the “hot-spots” (see Kretschmer et al. 2003), is one of the main long-term objectives of INTEGRAL, since it will provide the most accurate picture of recent star formation in the Milky Way (see contributions by Diehl et al. and Hartmann et al., this volume). On the other hand, 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 region 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 (see contribution by Knödlseder et al. in this volume).

The Vela region offers the opportunity to measure...
Clayton (1982) pointed out that SNII explosions still quite large and do not allow to conclude yet. Uncertainties in the corresponding stellar yields are expected gamma-ray line flux ratio of $^{59}$Fe(n,γ)$^{60}$Fe (Ali. Heger, private communication).

Figure 8. Radial profiles of $^{26}$Al (solid curve) and $^{60}$Fe (dashed curve) in a 25 $M_{\odot}$ star (from Rauscher et al. 2002). The dotted curve is also for $^{60}$Fe and it is obtained by reducing by a factor of 2 the cross section of $^{59}$Fe(n,γ)$^{60}$Fe (Ali. Heger, private communication).

(or put upper limits on) $^{26}$Al yields from individual sources. The morphology of the rather extended 1.8 MeV emission detected by COMPTEL (Diehl 2002) 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 nucleosynthesis models (see contribution by Mowlavi et al. in this volume).

It is not yet clear whether the majority of observed $^{26}$Al originates from the winds of the most massive stars (i.e. above 30 $M_{\odot}$, evolving as Wolf-Rayet stars) or from the explosions of less massive stars (i.e. in the 10-30 $M_{\odot}$ range, exploding as SNII); the uncertainties in the corresponding stellar yields are still quite large and do not allow to conclude yet.

Clayton (1982) pointed out that SNII explosions produce another relatively short lived radioactivity, $^{60}$Fe (lifetime ~2 Myr). Since WR winds do not eject that isotope, the detection of its characteristic gamma-ray lines in the Milky Way would constitute a strong argument for SNII being at the origin of $^{26}$Al. Based on detailed nucleosynthesis calculations of SNII (from Woosley and Weaver 1995, hereafter WW95) Timmes et al. (1995) found that the expected gamma-ray line flux ratio of $^{60}$Fe/$^{26}$Al (for each of the two lines of $^{60}$Fe) is 0.16, if SNII are the only sources of $^{26}$Al in the Milky Way.

The Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) detected the galactic $^{26}$Al emission at a flux level compatible with previous observations (Smith 2003). Recently, Smith (2004) reported the first ever detection of the Galactic $^{60}$Fe gamma-ray lines with RHESSI. A reanalysis of the data (see contribution by Smith, this volume) leads to a marginal significance of the detection (2.6 $\sigma$) and to a line flux ratio $^{60}$Fe/$^{26}$Al of 0.10 (for each $^{60}$Fe line), i.e. slightly lower than predicted by Timmes et al (1995) on the basis of WW95 nucleosynthesis calculations.

However, more recent studies of SNII nucleosynthesis (Rauscher et al. 2002, hereafter RHHW02; and Limongi and Chieffi 2003, hereafter LC03) produce different yields than WW95 (more $^{60}$Fe and less $^{26}$Al); in particular, a large amount of $^{60}$Fe is produced in the He-layer (Fig. 8), probably due to the different nuclear reaction rates used in the new calculations. As a result, the $^{60}$Fe/$^{26}$Al ratio turns out to be considerably higher than the one found in Timmes et al. (1995).

Figure 9. The expected ratio of $^{60}$Fe/$^{26}$Al decays (for each of the two $^{60}$Fe lines), convolved with a Salpeter stellar Initial Mass Function, is shown as a function of the upper stellar mass limit of the convolution integral. The four curves correspond to the four different sets of stellar yields, with their thick portions corresponding to the mass range covered in those works (see text). The dotted horizontal line at 0.10 is the $^{60}$Fe/$^{26}$Al line flux ratio reported by RHESSI (Smith, this volume) or, perhaps, an upper limit on that ratio. Filled pentagons mark the upper mass in each of the four studies; all recent calculations predict much higher values than the older calculations of WW95 and the value of RHESSI. Only by taking into account the $^{26}$Al yields of massive Wolf-Rayet stars (thin portion of the curves beyond the masses indicated by the filled pentagons, obtained by adding data on $^{26}$Al from WR stars from Meynet et al. 1997) one may obtain $^{60}$Fe/$^{26}$Al ratios compatible with the RHESSI results.

Prantzos (2004) compared the new yields with observations, after convolving with a stellar Initial Mass Function (IMF). The results are plotted in Fig. 9. In the case of LC03 two curves are shown: LC03I corresponds to the high $^{60}$Fe yields (low explosion
of solar initial metallicity by Meynet et al. (1997),

Adopting the star (i.e. up to the final explosion) exists up to now. For the complete evolution of a massive, mass losing, out of the star. Unfortunately, no consistent model stellar core before the final explosion and never get.

$^{26}$Al flux similar to the one of $^{26}$Fe. In stars with Fe would be detected with a line flux similar to the one of $^{26}$Al. Obviously, another source of $^{26}$Al is required, producing much smaller $^{60}$Fe/$^{26}$Al ratios than the SNII.

Assuming that the recent theoretical results are not to be substantially revised in the future and that the RHESSI result is confirmed, what are the implications for our understanding of the origin of $^{26}$Al? The obvious conclusion is that the bulk of galactic $^{26}$Al, detected by various instruments including RHESSI, is not produced by the source of $^{60}$Fe: if this were the case, then $^{60}$Fe would be detected with a line flux similar to the one of $^{26}$Al. Obviously, another source of $^{26}$Al is required, producing much smaller $^{60}$Fe/$^{26}$Al ratios than the SNII.

The obvious candidate source is Wolf-Rayet stars, as has been argued in many places over the years (e.g. Dearborn and Blake 1985, Prantzos and Cassé 1986, Prantzos 1993, Prantzos and Diehl 1996, Meynet et al. 1997, Knödlseder 1999). The winds of those massive, mass losing stars, eject large amounts of $^{26}$Al produced through H-burning in the former convective core, before its radioactive decay. In stars with no mass loss, those quantities of $^{26}$Al decay inside the stellar core before the final explosion and never get out of the star. Unfortunately, no consistent model for the complete evolution of a massive, mass losing, star (i.e. up to the final explosion) exists up to now.

Adopting the $^{26}$Al yields of non-rotating WR stars of solar initial metallicity by Meynet et al. (1997), which concern stars in the 25-120 M$_\odot$ mass range, and combining them with the aforementioned SNII yields (see Fig. 10), one obtains the $^{60}$Fe/$^{26}$Al line flux ratio produced by the total mass range of massive stars, during all the stages of their evolution; this is expressed in Fig. 9 by the continuation of the four theoretical curves above the masses indicated by the filled pentagons. It can be seen that the RHESSI result is recovered in that case, provided that at least half of $^{26}$Al originates from WR stars (in the case of LC03L), or even that 80% of $^{26}$Al originates from WR stars (in the case of RHHW02 or LC03H).

Those arguments point towards WR stars as major sources of $^{26}$Al in the Milky Way. However, the situation is far from clear yet, because the WR stellar yields of $^{26}$Al depend strongly on metallicity. In the case of non rotating stellar models that dependence is $\propto Z^2$, according to Meynet et al. (1997). The rotating models of WR stars, currently calculated by the Geneva group (Meynet and Maeder 2003) show that rotation considerably alleviates the need for high mass loss rates, while at the same time leading to the production of even larger $^{26}$Al yields than the non-rotating models (Vuissiez et al. 2003, calculations for rotating stars); however, the observed $^{26}$Al distribution (same points as in upper panel) is flatter than the expected one in that case.
metallicity \((\propto Z^{1.5})\) than the non rotating ones.

In both cases, that metallicity dependence of the 26\(^{}\text{Al}\) yields of WR stars, combined with the radial profiles of star formation rate (SFR) and of metallicity in the Milky Way (see Fig. 11, upper panel) suggest that the resulting radial profile of 26\(^{}\text{Al}\) should be much steeper than the one actually observed. The latter, derived from COMPTEL observations (Knödlseder 1997) appears in Fig. 11 (lower panel) and is clearly flatter than the product SFR\(\times Z^{1.5}\) (as already noticed in Prantzos 2002). Similar conclusions are reached if the longitude, rather than radial, profiles of 26\(^{}\text{Al}\), metallicity and SFR are considered.

Thus, almost twenty years after its discovery, the 26\(^{}\text{Al}\) emission of the Milky Way has not yet found a completely satisfactory explanation. Indeed, the recent observational (COMPTEL, RHESSI) and theoretical (RHHW02, LC03, Vuissoz et al. 2003) results have made the puzzle even more complex than before. The solution will obviously require progress in both theory and observations. From the theory point of view, detailed nucleosynthesis calculations of mass losing and rotating stars up to the final explosion in the mass range 12-100 M\(_{\odot}\) and for metallicities up to 3 Z\(_{\odot}\) will be required; furthermore, the uncertainties still affecting the reaction rates of \(^{22}\text{Ne}(\alpha,n)\) (major neutron producer during He burning in massive stars) and \(^{56}\text{Fe}(n,\gamma)\)\(^{57}\text{Fe}\) will have to be substantially reduced. From the observational point of view, the radial distributions of both 26\(^{}\text{Al}\) and \(^{60}\text{Fe}\) will be needed; such distributions will probably be available if the operation of INTEGRAL is prolonged for a few years beyond its nominal 2-year mission (see contribution by C. Winkler, this volume).

4. \textbf{POSITRON ANNIHILATION IN THE GALAXY}

The first \(\gamma\)-ray line ever detected outside the solar system was the 511 keV line of electron-positron annihilation (Johnson et al. 1972, Leventhal et al. 1978). Observations by various instruments in the 90's established that the line is not variable (at least in a \(\sim 10\) year period), that its spatial distribution is apparently dominated by a bulge-like component and that the overall spectrum suggests a large positronium fraction of 0.93 (see Kinzer et al. 2001 and references therein). The 511 keV flux detected by \(\gamma\)-ray spectrometers (HEAO-3, GRIS, HEXAGONE, TGRS) in the central Galactic sterad was found to be \(\sim 10^{-3}\) ph/cm\(^2\)/s, corresponding to a steady state production rate of \(10^{43}\) e\(^+\) s\(^{-1}\).

Observations during the early mission phase of INTEGRAL broadly confirm that picture. Analysis of SPI data (Knödlseder et al. 2003, Jean et al. 2003, contribution by Jean et al. this volume) finds a rather narrow line (FWHM=3 keV), excludes a point source in the Galactic Center (GC), and finds that the emission is bulge-like (best fit with a Gaussian of FWHM=9\(^{\circ}\)). The non-detection of a disk emission up to now imposes a model-dependent lower limit on the bulge/disk ratio of 0.4-0.8 (see also contribution by Weidenpöiter et al. this volume). The detected flux of \(9.9^{+4.7}_{-2.1}\) \(\times 10^{-4}\) ph/cm\(^2\)/s is compatible with previous measurements.

Possible sources of Galactic positrons have been studied in several works up to now (e.g. Dermer and Murphy 2001 and references therein). Most prominent among them seems to be the \(\beta^+\)-radioactivity of supernovae (see Table 1) and in particular of SNIa. On the other hand, the already detected emission of 26\(^{}\text{Al}\) in the Galaxy (Sec. 3) implies that this radioactive nucleus contributes a non-negligible fraction of the Galactic positron production rate. A thorough analysis of the supernova contribution to positron production in the Galaxy has been done by Milne et al. (1999a). Their conclusion was that the decay of \(^{56}\text{Co}\) from the total Galactic population of SNIa may produce \(\sim 10^{43}\) e\(^+\) s\(^{-1}\), and that this rate could explain about half of the total Galactic 511 keV emission as measured by OSSE, SMM and TGRS.

The improved spatial (and spectral) resolution of SPI gives a dramatic new twist to the issue of Galactic positrons, because it is clear now that \(\sim 10^{44}\) e\(^+\) s\(^{-1}\) are required to be produced in the bulge alone, not in the whole Milky Way (unless a mechanism is found to channel all positrons from the disk to the bulge).

The positron production rate from SNIa in the bulge is

\[
R = MFN
\]

where: \(M\) is the mass of the bulge, \(F\) is the SNIa frequency per unit mass in a bulge-like system, \(N\) is the number of positrons ejected by a typical SNIa. Typical values for those parameters are: \(M=1.5^{+0.5}_{-0.5}\) 10\(^{10}\) M\(_{\odot}\) (e.g. Launhardt et al. 2002), \(F=0.22^{+0.07}_{-0.07}\) SNIa per 10\(^{10}\) M\(_{\odot}\) per millenium (Cappellaro et al. 2003, assuming that the bulge is of intermediate type, between E0 and Sa) and \(N=8^{+5}_{-1}\) 10\(^{52}\) positrons (Milne et al. 1999b, i.e. the \(^{56}\text{Co}\) positron escape fraction is \(\sim 3\%\)). With those numbers one gets \(R \sim 0.8\) 10\(^{42}\) e\(^+\) s\(^{-1}\), i.e. a production rate about 12 times lower than suggested by the SPI data analysis. The expected contribution from other radioactivities (\(^{44}\text{Ti}\) from SN, 26\(^{}\text{Al}\) from massive stars, \(^{22}\text{Na}\) from novae) is too low to account for the missing amount of positrons.

It should be stressed that the uncertainties on \(F\) and \(N\) could be considerably larger than quoted in the previous paragraph. Indeed, the fact that SNIa have not been detected up to now in the bulges of spirals (Wang et al. 1997) suggests that important selection biases, e.g. extinction, may affect the results of current surveys.

On the other hand, the value of \(N\) has been empirically derived from the late lightcurves of SNIa (Milne et al. 1999b). This estimate is on much more secure grounds than the theoretical estimates of Chan and Lingelfelter (1993). However, it may also be affected by uncertainties on any early escape of
| SOURCE            | MORPHOLOGY                                      | INTENSITY                     | COMMENTS                                      |
|-------------------|-------------------------------------------------|-------------------------------|-----------------------------------------------|
| SNIa radioactivity| Consistent with observations                     | ~10 times low                | Uncertainties (perhaps) underestimated        |
| LMXBs Outflows/jets| Seems OK, BUT dominated by few strong sources outside the bulge | Unknown, but does not seem unreasonable because $\rightarrow$ | Less than 1% of available energy required to form positrons |
| Hypernova(e)      | Improbable (how to fill the bulge with positrons?) | Not unreasonable, but very poorly constrained | More hypernovae expected in disk (molecular ring) |
| Dark Matter annihilation | Centered on GC, otherwise unknown | Unknown/ Unconstrained | Postulated light particle should be seen in LEP (if in Standard Model) |

Table 2. Candidate sources for positrons in Galactic bulge

Figure 12. Longitude distribution of galactic LMXBs (thick histogram) and HMXBs (thin histogram), from Grimm et al. (2002). The collective emissivity of LMXBs is $\sim 10$ times higher than the one of HMXBs and 100 times higher than required to produce $10^{43}$ e$^+$ s$^{-1}$. Even more speculative is the suggestion (Nomoto et al. 2001) that very energetic (and presumably aspherical) explosions of massive stars, known as “hypernovae” are at the origin of the 511 keV emission. This idea has been further elaborated in Cassé et al. (2004, see also contribution by Schanne et al. this volume). The observed constraints on 511 keV intensity could be satisfied in that case, since such explosions are expected to produce large amounts of $^{56}$Ni (see Fig. 3, and SN1998bw in particular) along the rotation axis, thus making easier the escape of positrons. However, there is no quantitative evaluation yet of the positron escape fraction in such sources, and any theoretical one will suffer from the same large uncertainties as the analysis of Chan and Lingenfelter (1993) on SNIa; empirical evaluation will require much larger statistical samples and longer observations of hypernovae than presently available. Independently of that, the idea has several shortcomings: it is difficult to imagine how the positrons of a single (or a few) explosion(s) could fill the bulge; and it is statistically improbable that such events are not detected in the Milky Way disk (for instance in the molecular ring), where the star formation rate is much higher than in the galactic center or bulge and where all conditions for positron slow down and annihilation are fulfilled.

Finally, annihilation of a rather special kind of light dark matter particles has been recently proposed as the source of galactic positrons (Boehm et al. 2003,
contribution by Cassé et al. this volume). The proposed particles are quite light (in the 1-100 MeV range) so that their annihilation does not produce undesirable high energy gamma-rays, and in that respect they do not correspond to the most commonly discussed dark matter candidate, which has mass in the GeV to TeV range. Moreover, rather special properties are required for such light particles to justify why they have escaped detection up to now in accelerators such as the LEP. It is hard to evaluate the plausibility of that hypothesis, since the required properties of the source (i.e. density profile, annihilation cross-section) are completely unknown/unconstrained; in fact, the observed properties of the 511 keV emission (intensity and density profile) are used in Boehm et al. (2003) in order to derive the properties of the dark matter source of positrons.

Further observations by INTEGRAL will help, since it is expected that the Galactic disk will sooner or later manifest itself in the light of 511 keV photons. Preliminary hints for disk 511 keV emission were found in OSSE’s data (e.g. Kinzer et al. 2001, Milne et al. 2002). The observed disk emission of $^{26}$Al at 1.8 MeV puts a lower limit on the positron production rate of the disk; observations will establish whether those positrons annihilate locally (i.e. whether the steady-state assumption is locally valid) or whether they escape in the halo to annihilate at higher latitudes. In that respect, the Cygnus region, one of the most prominent “hot-spots” in COMPTEL’s 1.8 MeV map (see Fig. 7) is a most promising target.

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