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Cosmic radioactivities

Marcel Arnould[a,1], Nikos Prantzos[b,2]

[a]Institut d'Astronomie et d'Astrophysique, Université Libre de Bruxelles, C.P. 226, Bd. du Triomphe, B-1050 Brussels, Belgium
[b]Institut d'Astrophysique de Paris, 98 bis Bd. Arago, F-75014 Paris, France

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Abstract

Radionuclides with half-lives ranging from some years to billions of years presumably synthesized outside of the solar system are now recorded in ''live'' or ''fossil'' form in various types of materials, like meteorites or the galactic cosmic rays. They bring specific astrophysical messages, the deciphering of which is briefly reviewed here, with special emphasis on the contribution of Dave Schramm and his collaborators to this exciting field of research. Short-lived radionuclides are also present in the Universe today, as directly testified by the γ-ray lines emitted by the de-excitation of their daughter products. A short review of recent developments in this field is also presented. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

When Marie and Pierre Curie discovered just one century ago the mysterious phenomenon of radioactivity, they certainly did not imagine that they had opened the way to a better understanding of many facets of the Universe! Dave Schramm has entered this way, clearing many of its misty sections with his uncommon enthusiasm and energy, and with a remarkably vivid view of the astrophysical potentialities along the road. This contribution is a tribute to this aspect of Dave's mutiple activities, and in particular to his important contribution to the unravelling of the astrophysical messages from long- and short-lived radionuclides. We will in particular briefly review some selected aspects of nucleo-cosmochronology, as well as of the field of the isotopic anomalies of radionuclidic origin. Additionally, the decay of certain radionuclides manifests itself quite spectacularly through the emission of de-excitation lines in the γ-ray domain. The study of these radionuclides offers invaluable information on their production sites and is the subject of γ-ray line astronomy, a recently developed astrophysical discipline which we review in the last section of this paper.

In contrast, we will not deal here with the very interesting subject of the production of a large variety of radionuclides in terrestrial or solar-system extra-terrestrial matter bombarded by galactic cosmic rays or solar energetic particles. This spallative

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[1] E-mail: marnould@astro.ulb.ac.be
[2] E-mail: prantzos@iap.fr

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production is of importance for the deciphering of the record of these energetic particles, and in particular of the time variations of their fluxes, but its interest goes well beyond astrophysics or planetology. The reader is referred to e.g. Michel (1998) for a review and some references.

2. Cosmochronometry

The dating of the Universe and of its various constituents, referred to as ''cosmochronology'', is one of the tantalizing tasks in modern science. This field is in fact concerned with different ages, each one of them corresponding to an epoch-making event in the past (e.g. Vangioni-Flam et al. (1990) for many contributions on this subject, and especially Dave's contribution (Schramm, 1990)). They are in particular the age of the Universe T_U, of the globular clusters T_{GC}, of the Galaxy [as (a typical?) one of many galaxies] T_G, of the galactic disc T_{disc}, and of the non-primordial nuclides in the disc T_{nuc}, with $T_U \gtrsim T_{GC} \approx (\gtrsim ?)\, T_G \gtrsim T_{disc} \approx T_{nuc}$. As a consequence, cosmochronology involves not only cosmological models and observations, but also various other astronomical and astrophysical studies, and even invokes some nuclear physics information.

The cosmological models can help determining T_U, as well as, to some extent at least, T_{GC} and T_{disc} (e.g. Arnould & Takahashi (1990a), Fowler & Meisl (1986), Tayler (1986) for brief accounts). The T_{GC} or T_{disc} values have also been evaluated from the use of the Herztsprung-Russell diagram (HRD) (e.g. Jimenez (1998), VandenBerg et al. (1996) for recent reviews), or of so-called ''luminosity functions,'' which provide the total number of stars per absolute magnitude interval as a function of absolute magnitudes. In particular, the luminosity function of white-dwarf stars has been proposed as a priviledged T_{disc} evaluator (e.g. Hernanz et al., 1994; Oswalt et al., 1996). Nucleo-cosmochronological techniques have also been developed in order to evaluate T_{nuc}, and are briefly discussed below. Each of these methods has advantages and weaknesses of its own, as briefly reviewed by e.g. Arnould & Takahashi (1990a).

2.1. ''Long-lived'' nucleo-cosmochronometers: generalities

The dating method that most directly relates to nuclear astrophysics is referred to as ''nucleo-cosmochronology.'' It primarily aims at determining the age T_{nuc} of the nuclides in the galactic disc through the use of the observed bulk (meteoritic) abundances of radionuclides with lifetimes commensurable with presumed T_{disc} values (referred to in the following as ''long-lived'' radionuclides). Consequently, it is hoped to provide at least a lower limit to T_{disc}. The most studied chronometries involve ^{187}Re or the trans-actinides ^{232}Th, ^{235}U and ^{238}U.

In order to establish a good chronometry based on these radioactive nuclides, one needs to have firstly a good set of input data concerning (isotopic) abundances and nucleosynthesis yields, in addition to the radioactive half-lives. Another issue concerns the necessity, and then the possibility, of using detailed models for the chemical evolution of the Galaxy in order to gain a reliable nucleo-cosmochronological information if indeed the bulk solar-system composition witnesses the perfect mixing of a large number of nucleosynthetic events. The status of these various requirements is briefly examined in the following sections for several cosmic clocks.

2.1.1. The trans-actinide clocks

The familiar long-lived ^{232}Th–^{238}U and ^{235}U–^{238}U chronometric pairs (Fowler & Hoyle, 1960) are developed on grounds of their abundances at the time of solidification in the solar system some 4.56×10^9 yr ago. This information is obtained by extrapolating back in time the present meteoritic content of these nuclides. If the so-derived abundances are affected by some uncertainties, these are not, however, the main problems raised when attempting to use these radionuclides as reliable nuclear clocks. Their usefulness in this respect indeed depends in particular on the availability of precise production ratios. Such predictions at the level of accuracy needed for getting a truly useful chronometric information are out of reach at the present time. One is indeed dealing with nuclides that can be produced by the r-process only, which suffers from very many astrophysics and nuclear physics problems, in spite of much effort by many researchers, including Dave and his collaborators (e.g. Meyer (1994) for relevant references). The r-process problems are particularly acute for the Th and U isotopes referred to above. They are indeed the only naturally-occurring nuclides beyond ^{209}Bi, so that any extrapolation relying on semi-empirical analyses and fits of the solar r-process abundance curve is in danger of being especially unreliable. The difficulty is further reinforced by the fact that most of the r-process precursors of U and Th are nuclei that are unknown in the laboratory, and will remain so for a long time to come. Theoretical predictions of properties of relevance, like masses, β-decay strength functions and fission barriers, are extremely difficult, particularly as essentially no calibrating points exist. This problem would linger even if a realistic r-process model were given, which is not the case at the present time (e.g. Arnould & Takahashi, 1999). Last but not least, most of the tremendous amount of work devoted in the past to the trans-actinide chronometry has adopted simple functionals for the time dependence of the r-process nucleosynthesis rate (a.k.a. ''Mickey Mouse Models'' coined by Pagel, 1990) with little consideration of the chemical evolution in the solar neighbourhood. This view, which originated almost 4 decades ago (Fowler & Hoyle, 1960), has had (and still has) a few sympathisers indeed (e.g. Cowan et al. (1991); also Arnould & Takahashi (1999) for some references).

The necessity of the development of the long-lived chronometers in the framework of models for the chemical evolution of the Galaxy has been first pointed out by Tinsley (1977); Tinsley (1980). The introduction of nucleo-cosmochronological considerations in such models is not a trivial matter, however. The intricacies come in particular from ''astration'' effects, which have to do with the fate of the chronometers once absorbed from the interstellar medium by the stars at their birth (e.g. Yokoi et al., 1983). However, Dave, in collaboration with Wasserburg (Schramm & Wasserburg, 1970), has made an important contribution to nucleo-cosmochronology by showing that one can make the economy of these chemical evolution models as long as a mere determination of *age limits* could satisfy one's curiosity. This interesting so-called ''model-independent approach'' has led to the conclusion that $9 \lesssim T_{\rm nuc} \lesssim 27$ Gyr (Meyer & Schramm, 1986).

There has also been an attempt to develop a Th-chronometry (Pagel, 1989) on grounds of the relative abundances of Th and Eu (which is presumed to be dominantly produced by the r-process) observed at the surface of stars with various metallicities[3]. Under the assumption, which may sound reasonable but has not at all to be taken for granted, that any r-process in the past has produced Th and Eu with a constant solar-system ratio, the age determination is reduced to the problem of mapping the metallicity on time through a chemical evolution model. High-quality observational Th/Eu abundance data in stars of various metallicities are accumulating (Da Silva et al., 1990; François et al., 1993; Sneden et al., 1996). In spite of some attempts (Cowan et al., 1997), much remains to be done in the difficult task of deriving $T_{\rm nuc}$ from these observations.

The Th-chronometry could be put on safer grounds if the Th/U ratios would be known in a variety of stars with a high enough accuracy. These nuclides are indeed likely to be produced simultaneously, so that one may hope to be able to predict their production ratio more accurately than the Th/Eu one. Even in such relatively favourable circumstances, one would still face the severe question of whether Th and U were produced in exactly the same ratio in presumably a few r-process events (a single one?) that have contaminated the material from which metal-poor stars formed. Even if this ratio turns out to be the same indeed, its precise value remains to be calculated (see, e.g., Arnould & Takahashi (1990b) for an illustration of the dramatic impact of a variation in the predicted Th/U ratio on predicted ages).

2.1.2. The ^{187}Re–^{187}Os chronometry

First introduced by Clayton (1964), the chronometry using the ^{187}Re–^{187}Os pair is able to avoid the difficulties related to the r-process modelling. True, ^{187}Re is an r-nuclide. However, ^{187}Os is not produced directly by the r-process, but indirectly

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[3] Originally, an attempt was made to use the observed Th/Nd ratios (Butcher, 1987), albeit the disadvantage of Nd being possibly produced also by the s-process.

via the β^--decay of ^{187}Re ($t_{1/2} \approx 43$ Gyr) over the galactic lifetime. This makes it in principle possible to derive a lower bound for $T_{\rm nuc}$ from the mother-daughter abundance ratio, provided that the "cosmogenic" ^{187}Os component is deduced from the solar abundance by subtracting its s-process contribution. This chronometry is thus in the first instance reduced to a question concerning the s-process. Other good news come from the recent progress made in the measurement of the abundances of the concerned nuclides in meteorites (e.g. Faestermann (1998) for references). This input is indeed essential also for the establishment of a reliable chronometry.

Although the s-process is better understood than the r-process, this chronometry is facing specific problems. They may be summarized as follows (see e.g. Takahashi (1998) for a short account): (1) the evaluation of the ^{187}Os s-process component from the ratio of its production to the one of the s-only nuclide ^{186}Os is not a trivial matter, even in the simple local steady-flow approximation (constancy of the product of the abundances by the stellar neutron capture rates over a restricted A-range). The difficulty relates to the fact that the ^{187}Os 9.75 keV excited state can contribute significantly to the stellar neutron capture rate because of its thermal population in s-process conditions ($T \gtrsim 10^8$ K) (e.g. Winters et al., 1986; Woosley & Fowler, 1979). The ground-state capture rate measured in the laboratory has thus to be modified by a theoretical correction. In addition, the possible branchings of the s-process path in the $184 \leq A \leq 188$ region may be responsible of a departure from the steady-flow predictions for the ^{187}Os/^{186}Os production ratio (e.g. Arnould et al., 1984; Käppeler et al., 1991); and (2) at the high temperatures, and thus high ionisation states, ^{187}Re may experience in stellar interiors, its β-decay rate may be considerably, and sometimes enormously, enhanced over the laboratory value by the bound-state β-decay of its ground state to the 9.75 keV excited state of ^{187}Os (e.g. Yokoi et al., 1983). Such an enhancement has recently been beautifully confirmed by the measurement of the decay of fully-ionised ^{187}Re at the GSI storage ring (Bosch et al., 1996; Kienle et al., 1998). The inverse transformation of ^{187}Os via free-electron captures is certainly responsible for additional corrections to the stellar ^{187}Re/^{187}Os abundance ratio (e.g. Arnould, 1972; Yokoi et al., 1983). Further complications arise because these two nuclides can be concomitantly destroyed by neutron captures in certain stellar locations (Yokoi et al., 1983).

All the above effects have been studied in the framework of realistic evolution models for $1 \lesssim M \lesssim 50\, M_\odot$ stars and of a galactic chemical evolution model that is constrained by observational data in the solar neighbourhood (Takahashi, 1998; Takahashi et al., 1998). This work, which is an up-date of Yokoi et al. (1983) with regards to meteoritic abundances, nuclear input data, stellar evolution models and observational constraints, concludes that $T_{\rm nuc} \approx 15 \pm 3$ Gyr. Even lower ages of about 9 Gyr, as derived from the model-independent approach (Schramm & Wasserburg, 1970; Schramm, 1990) (Section 2.1.1), can not conclusively be excluded within the remaining uncertainties in the chemical evolution model parameters.

These results may imply that the ^{187}Re–^{187}Os chronometry has not yet much helped narrowing the age range derived from other methods. There is still ample room for improvements, however, and there is reasonable hope that the Re–Os chronometry will be able to set some meaningful limits on $T_{\rm nuc}$ in a near future, and independently of other methods.

2.1.3. ^{176}Lu, a long-lived s-process radionuclide

The long-lived ^{176}Lu ($t_{1/2} = 41$ Gyr) has the remarkable property of being shielded from the r-process, and thus to be a pure s-process product. It has been proposed by Dave and his collaborators (Audouze et al., 1972), and independently by Arnould (1973), to be a potential chronometer for the s-process, the other long-lived radionuclides probing the r-process instead. These early works pointed out some possible uncertainties in the solar ^{176}Lu abundance, as well as in its production predicted from s-process models. The latter problem relates directly to the branching in the s-process path due to the 125 keV ^{176}Lu$^{\rm m}$ isomeric state. More specifically, the two different paths ^{175}Lu(n,γ)^{176}Lu$^{\rm g}$(n,γ)^{177}Lu(β^-)^{177}Hf and ^{175}Lu(n,γ)^{176}Lu$^{\rm m}$(β^-)^{176}Hf(n,γ)^{177}Hf may well develop during a s-process (^{176}Lu$^{\rm g}$ designates the ^{176}Lu ground state). The resulting ^{176}Lu$^{\rm g}$/^{176}Hf production ratios depend on the relative importance of these two branchings, and thus mainly on the relative population of the ground and isomeric ^{176}Lu states. Two limiting situations are relatively simple to handle. The first one is obtained if ^{176}Lu^{g} and ^{176}Lu^{m} have no time in a given astrophysical environment for being connected electromagnetically. This situation is made plausible by the large difference in the spin and K quantum number of the two states. In such conditions, the relative importance of the two s-process branches is just given by the ^{175}Lu(n,γ)^{176}Lu^{m}/^{175}Lu(n,γ)^{176}Lu^{g} cross section ratio, the value of which can be obtained from experiments. The other extreme is obtained if ^{176}Lu^{g} and ^{176}Lu^{m} are coupled electromagnetically strongly enough for the relative populations of these two states to be ‘‘thermalized’’, i.e. follow the rules of statistical equilibrium. In such conditions, the relative importance of the two s-process branches is essentially governed by temperature, as is the effective decay rate of the thermalized ^{176}Lu.

Since the pioneering studies mentioned above, much work has been devoted to the question of the possibility of thermalization of the ^{176}Lu isomeric and ground states in astrophysical plasmas, and to the measurement of the neutron capture cross sections needed for the calculation of the s-process ^{176}Lu/^{176}Hf production ratio (e.g. Klay et al. (1991), Lesko (1991), and references therein). From these efforts, it is generally concluded nowadays that the ^{176}Lu^{g} s-process yields are so sensitive to temperatures and neutron densities that they cannot be evaluated precisely enough for chronological purposes. Instead, ^{176}Lu^{g} could rather be considered as a s-process thermometer.

3. The message from extinct ‘‘short-lived’’ radionuclides

The discovery of isotopic anomalies attributed to the decay in some meteoritic material of now extinct radionuclides with half-lives in the approximate $10^5 \lesssim t_{1/2} \lesssim 10^8$ yr range (referred to in the following as ‘‘short-lived’’ radionuclides) has broadened the original astrophysical interest for cosmic radioactivities. Even the ‘‘ultra-short’’ radionuclides ^{22}Na ($t_{1/2} = 2.6$ yr) and ^{44}Ti ($t_{1/2} \approx 60$ yr; see Wietfield et al. (1999)) are likely to have left their signatures in some meteorites. The interpretation of the message from these anomalies has been the focus of much work and excitement.

One important issue raised by the extinct radionuclides concerns their presence in the early solar system in ‘‘live’’ form, or just in the form of their daughter products (‘‘fossils’’). In the first case, the anomalies have of course to be located in solar-system indigenous solids, while they have to be found in alien (presolar) material in the second situation. At present, there is clear evidence that meteorites contain both live and fossil signatures of short-lived nuclides, and the messages they carry are quite different indeed. In contrast, the meteoritic content of the ultra-short-lived nuclides has obviously to be of fossil nature, in view of the lifetimes involved.

3.1. Live short-lived radionuclides in the early solar system

At the end of the sixties, Dave and his collaborators (Schramm et al., 1970) have contributed in an important way to the pioneering searches for the signatures of extinct radionuclides in meteorites (e.g. Wasserburg & Papanastassiou (1982) for a historical account) by establishing techniques for the high precision measurement of the Mg isotopic composition in order to search for ^{26}Mg excesses due to the ^{26}Al decay in meteorites of different types and in lunar samples. From this study, it was concluded that the upper limits on the $(^{26}\mathrm{Al}/^{27}\mathrm{Al})_0$ ratio[4] in the analyzed materials was ranging from well below 10^{-6} to about 2×10^{-6}. It is established by now that ^{26}Al has been live in the solar system at a canonical level of $(^{26}\mathrm{Al}/^{27}\mathrm{Al})_0 \approx 2 \times 10^{-5}$ (MacPherson et al., 1995). Persuasive evidence for the existence of other live radionuclides has accumulated, and concerns nowadays ^{53}Mn, ^{60}Fe, ^{107}Pd, ^{129}I, ^{146}Sm and ^{244}Pu. This is also likely the case for ^{182}Hf and ^{41}Ca, the presence of which has recently been found to be correlated with the one of ^{26}Al in some primitive meteorites (Sahijpal et al., 1998). Some weaker evidence has been gathered about ^{36}Cl, ^{92}Nb, ^{99}Tc and ^{205}Pb (see, e.g., Podosek & Nichols (1997) for a review and references).

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[4] Here and in the following, the subscript 0 refers to the start of solidification in the solar system some 4.56×10^9 yr ago.

The demonstrated existence of short-lived radionuclides in live form in the early solar system can usefully constrain the chronology of the nebular and planetary events at that epoch (e.g. Podosek & Nichols (1997) for details). From a more astrophysical point of view, these observations are generally considered to provide the most sensitive radiometric probes concerning discrete nucleosynthesis events that presumably contaminated the solar system at times between about 10^5 and 10^8 yr prior to the isolation of the solar material from the general galactic material. Of course, this statement assumes implicitly that the radionuclides of interest have not been synthesized in the solar system itself. Can such a local production scenario be rejected right the way? Clearly, a large variety of radionuclides are produced continuously in the present extraterrestrial solar system matter, as well as in terrestrial samples, by spallation reactions induced by Galactic Cosmic Rays (GCRs) or by Solar Energetic Particles (SEPs) (e.g. Michel, 1998). However, such a production cannot account for the abundances of extinct radionuclides derived from the observed isotopic anomalies mentioned above, at least if the spallation processes have operated in the early solar system at a level commensurable with their present efficiency. The only hope for a local production to be viable is thus to call for an enhanced spallation production which could be associated with the increased SEP production of the young Sun, especially in its T-Tauri phase. The various studies conducted along these lines reach the conclusion that it appears difficult to account for the production of the relevant short-lived radionuclides in proportions compatible with the observations (e.g. Podosek & Nichols (1997) for references; also Sahijpal et al. (1998)).

If indeed the short-lived radionuclides that have been present live in the early solar system are not of local origin, the message they carry on the chronology of the nucleosynthetic events responsible for a ‘‘late pollution’’ of the solar system can obviously not be extracted from the chemical evolution models needed when one deals with long-lived chronometers. Instead, a scenario relying on a limited number of events has to be constructed. Such a ‘‘granular’’ model has been tailored by Dave (Schramm, 1978), and made more specific with the so-called ‘‘Bing Bang’’ model (Reeves, 1978; Reeves, 1979), which envisions the contamination and formation of the solar system in an OB association during its approximate 10^7 yr lifetime. A chronology based on these granular chemical evolution models raises a series of important and difficult questions related in particular to the type of nucleosynthetic event(s) responsible for the contamination, the corresponding radionuclide yields, as well as the efficiency of the pollution. Dave has actively contributed at different levels to the scrutiny of these problems (e.g. Schramm (1978) for some references). He has in particular been very much concerned with the possible role supernovae have played in the production of short-lived radionuclides, as well as in their injection into the forming solar system. Under Dave’s supervision, Margolis (1979) has developed hydrodynamical simulations of the contamination of a proto-solar type cloud by the impacting (isotopically anomalous) gas or ‘‘shrapnel-like’’ grains of a supernova shell. At this occasion, grains have been shown to be more efficient contaminating agents than the gas as a result of their higher probability of penetration in the solar nebula, as well as of the reduced danger of having the isotopic anomalies washed out beyond recognition in the bulk nebular material before the start of the solar system solidification sequence (of course, this does not exclude grain vaporisation *during* the solidification, which seems to be requested by the analysis of the isotopic anomalies attributed to the radionuclide in situ decay). The priviledged role possibly played by grains was most welcome at a time Dave and his collaborators had studied in some detail the sequence of consensation of grains around exploding stars (Lattimer et al., 1978). At about the same time, the possible role in the supernova contamination efficiency of ‘‘fast moving knots’’ just discovered in the supernova remnant Cas A was stressed (Arnould & Nørgaard, 1978), and may be nicely complementary to the contaminating importance of grains. There is indeed mounting evidence that fast moving knots are priviledged locations of grain formation in supernova ejecta (Lagage et al., 1996). Certainly, the details of the contamination are still far from being settled. In any case, it seems highly plausible that the short-lived radionuclides have been distributed heterogeneously in the forming solar system (see also Podosek & Nichols, 1997). This complicated situation may affect quite negatively their chronological predictive virtues.

The possible role of supernovae in the pollution of the early solar system with short-lived radionuclides (along with other stable nuclides) has continued to be studied actively. Other types of contaminators have also been proposed, like novae or Asymptotic Giant Branch stars. Here, and in the spirit of the Bing Bang model, we briefly recall below that massive stars of the Wolf-Rayet type might also have been responsible for the production of a quite large suite of short-lived radionuclides, and of their injection into the forming solar system. We devote also a brief discussion to the short-lived radionuclides ^{146}Sm and ^{205}Pb which have been explored by Dave, and which have been the subject of some recent work.

3.1.1. WR stars: short-lived radionuclide contaminators of the early solar system?

Wolf-Rayet (WR) stars are fascinating objects that have a dramatic impact on their surroundings through their huge winds. They have been, and still are, the focus of much observational and theoretical efforts. Their main properties have been reviewed by Arnould et al. (1997a), and are not repeated here.

The production of short-lived radionuclides of cosmochemical interest by a large variety of WR stars has been calculated in the framework of detailed evolution models, and with the use of extended nuclear reaction networks (Arnould et al., 1997b). As the modelling of these stars is immensely simpler than the one of all the other short-lived radionuclide producers proposed up to now, the predicted WR yields are thus likely to reach a level of reliability that cannot be obtained in the other cases. In short, the main results obtained by Arnould et al. (1997b) are as follows:

1. The neutrons released by ^{22}Ne(α,n)^{25}Mg during the He-burning phase of the considered stars are responsible for a s-type process leading to the production of a variety of $A > 30$ radionuclides. In the absence of any chemical fractionation between the relevant elements, it is demonstrated that ^{36}Cl, ^{41}Ca and ^{107}Pd can be produced by this s-process in a variety of WR stars of the WC subtype with different initial masses and compositions at a *relative* level compatible with the meteoritic observations. For a $60\,M_\odot$ star with solar metallicity, Fig. 1 shows that this agreement can be obtained for a time $\Delta^* \approx 2 \times 10^5$ yr, where Δ^* designates the time elapsed between the last astrophysical event(s) able to affect the composition of the solar nebula and the solidification of some of its material (e.g. Wasserburg, 1985). More details concerning other model stars are given by Arnould et al. (1997b);
2. To the above list of radionuclides, one certainly has to add ^{26}Al, which is of crucial importance not only in cosmochemistry, but also for γ-ray astronomy (Section 4). A detailed discussion of its production by the MgAl chain of hydrogen burning has been conducted recently by Arnould et al. (1997b) and Meynet et al. (1997). Let us simply note here that the canonical value (^{26}Al/^{27}Al)$_0 = 5 \times 10^{-5}$ (MacPherson et al., 1995), while not reached in the $60\,M_\odot$ star displayed in Fig. 1, can be obtained from the winds of $M \geq 60\,M_\odot$ stars with $Z > Z_\odot$ under the same type of assumptions as the ones adopted to construct Fig. 1. Let us also note that the WR models can account for the correlation between ^{26}Al and ^{41}Ca observed in some meteorites (Sahijpal et al., 1998);
3. In contrast, too little ^{60}Fe is synthesized;
4. An amount of ^{205}Pb that exceeds largely the experimental upper limit set by Huey & Kohman (1972), but which is quite compatible with the value reported by Chen & Wasserburg (1987), is obtained not only for the model star displayed in Fig. 1, but also for the other cases considered by Arnould et al. (1997b). This high production appears in fact to be a distinctive prediction concerning WR stars, and a renewed search for its in situ decay in meteorites would be most valuable (Section 3.1.3);
5. More or less large amounts of ^{93}Zr, ^{97}Tc, ^{99}Tc and ^{135}Cs can also be produced in several cases, but these predictions cannot be tested at this time due to the lack of reliable observations.

It has to be remarked that the above conclusions are derived without taking into account the possible contribution from the material ejected by the eventual supernova explosion of the considered WR stars. This supernova might add its share of radionuclides

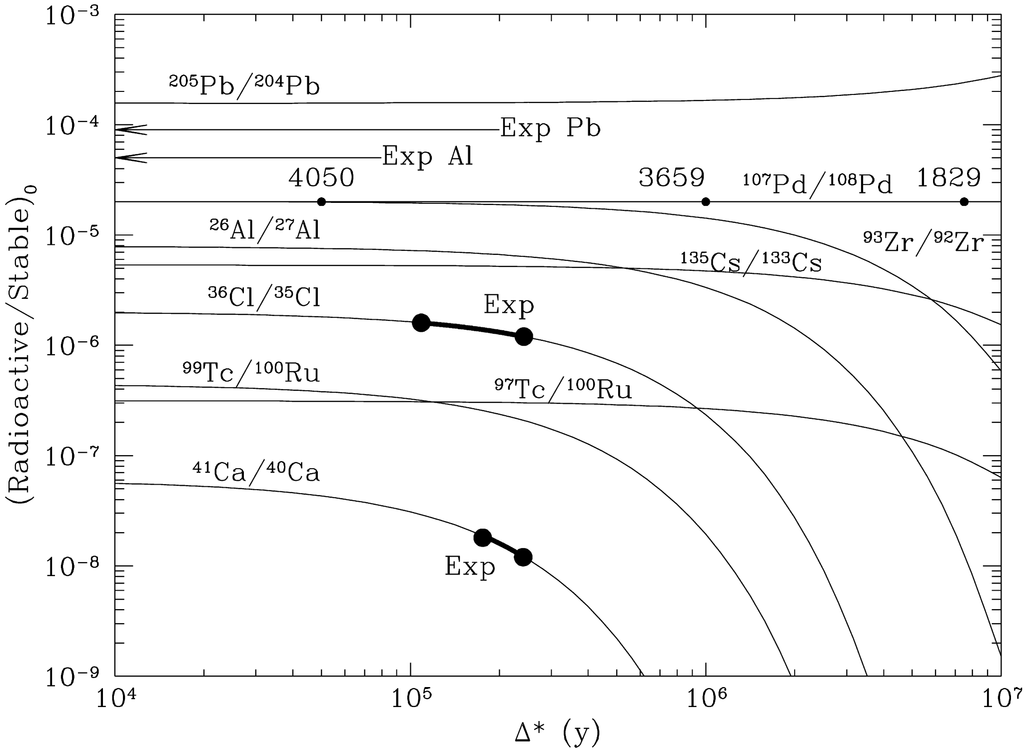

Fig. 1. Abundance ratios $(R/S)_0$ of various radionuclides R relative to stable neighbours S versus Δ^* (see main text) for a 60 $M_\odot$ model star with $Z = 0.02$. All the displayed ratios are normalized to $(^{107}\mathrm{Pd}/^{108}\mathrm{Pd})_0 = 2 \times 10^{-5}$ (e.g. Wasserburg, 1985) through the application of a common dilution factor $d(\Delta^*)$. The values of this factor are indicated on the Pd horizontal line for 3 values of Δ^*. Other available experimental data (labelled Exp) are displayed. They are adopted from MacPherson et al. (1995) for Al, Srinivasan et al. (1994) for Ca (see also Sahijpal et al., 1998), Murty et al. (1997) for Cl, and Huey & Kohman (1972) for Pb (see also Chen & Wasserburg, 1987), who propose the somewhat larger value $(^{205}\mathrm{Pb}/^{204}\mathrm{Pb})_0 \approx 3 \times 10^{-4}$ (not shown)) (see Arnould et al. (1997b) for more details).

that are not produced abundantly enough prior to the explosion. This concerns in particular ^{53}Mn, ^{60}Fe or ^{146}Sm. One has also to acknowledge that the above conclusions sweep completely under the rug the possible role of binarity in the WR yields. Its impact on the predicted ^{26}Al production and the additional level of uncertainty it generates have been explored by Langer et al. (1995).

From the results reported above, one can try estimating if indeed there is any chance for the contamination of the protosolar nebula with isotopically anomalous WR wind material at an *absolute* level compatible with the observations. In the framework of Fig. 1, this translates into the possibility of obtaining reasonable dilution factors $d(\Delta^*)$. A qualitative discussion of this highly complex question based on a quite simplistic scenario is presented by Arnould et al. (1997b). In brief, it is concluded that astrophysically plausible situations may be found in which one or several WR stars with masses and metallicities in a broad range of values could indeed account for some now extinct radionuclides that have been injected live into the forming solar system (either in the form of gas or grains). Of course, a more definitive conclusion would have to await the results of a more detailed model that takes into account the high complexity of the WR circumstellar shells, and of their interaction with their surroundings, demonstrated by observation and suggested by numerical simulations. Concomitantly, the possible role of WR stars, either isolated or in OB associations, as triggers of the formation of some stars, and especially of low-mass stars, should be scrutinized.

3.1.2. ^{146}Sm: a short-lived p-process radionuclide

There is now strong observational evidence for the existence in the early solar system of the two p-process radionuclides $^{92}\mathrm{Nb}^{\mathrm{g}}$ ($t_{1/2} = 3.6 \times 10^7$ yr) and ^{146}Sm ($t_{1/2} = 1.03 \times 10^8$ yr) (Harper (1996), and references therein). The case of $^{92}\mathrm{Nb}^{\mathrm{g}}$ has been discussed by Rayet et al. (1995), who conclude that various uncertainties in the level of production of this radionuclide make rather unreliable at this time the development of a ^{92}Nb-based p-process chronometry.

As far as ^{146}Sm is concerned, the study of its potential as a p-process chronometer has been pioneered by Dave in collaboration with Audouze (Audouze & Schramm, 1972). This work has triggered a series of meteoritic, nuclear physics and astrophysics investigations, which have helped clarifying many aspects of the question. In particular, the early uncertainties on the amount of ^{146}Sm that has been injected live into the solar system have been greatly reduced through several studies of the ^{142}Nd excess observed in certain meteorites as the result of the in situ ^{146}Sm α-decay. More specifically, it is concluded nowadays that $(^{146}\mathrm{Sm}/^{144}\mathrm{Sm})_0 = 0.008 \pm 0.001$, ^{144}Sm being the stable Sm p-isotope. One can attempt building up a p-process chronometry on this value if the corresponding isotopic production ratio can be estimated reliably enough at the p-process site.

Much work has been devoted to the modelling of the p-process in massive stars, and especially in Type II supernovae (e.g. Arnould et al., 1998b). In spite of this, the production ratio $P \equiv {}^{146}\mathrm{Sm}/{}^{144}\mathrm{Sm}$ remains quite uncertain, being estimated by Somorjai et al. (1998) to lie in the $0.7 < P < 2$ range in (spherically symmetric) Type II supernova models. This unfortunate situation relates in part to astrophysical problems, and in part to nuclear physics uncertainties, especially in the $^{148}\mathrm{Gd}(\gamma,\alpha)^{144}\mathrm{Sm}$ to $^{148}\mathrm{Gd}(\gamma,\mathrm{n})^{147}\mathrm{Gd}$ branching ratio (e.g. Rayet & Arnould, 1992), even if the prediction of this ratio has recently gained increased reliability. This improvement comes from the direct measurement of the $^{144}\mathrm{Sm}(\alpha,\gamma)^{148}\mathrm{Gd}$ cross section down to energies very close to those of direct astrophysical interest (Somorjai et al., 1998), complemented with a better nuclear reaction model (Arnould et al., 1998a). The resulting astrophysical rate is predicted to be 5 to 10 times lower than previous estimates in the temperature range of relevance for the production of the Sm p-isotopes. By application of the detailed balance theorem, the rate of the reverse $^{148}\mathrm{Gd}(\gamma,\alpha)^{144}\mathrm{Sm}$ of direct astrophysical interest is reduced accordingly. This implies a lowering of the ^{144}Sm production, and favours concomitantly the ^{146}Sm synthesis through the main production channel $^{148}\mathrm{Gd}(\gamma,\mathrm{n})^{147}\mathrm{Gd}(\gamma,\mathrm{n})^{146}\mathrm{Gd}(\beta^+)^{146}\mathrm{Sm}$. The net effect of the revised $^{148}\mathrm{Gd}(\gamma,\alpha)^{144}\mathrm{Sm}$ rate is thus an increase of the P values.

Other nuclear problems add to the uncertainty in the evaluation of P. As noted above, this concerns in particular the $^{148}\mathrm{Gd}(\gamma,\mathrm{n})^{147}\mathrm{Gd}$ reaction, for which no experimental information can be foreseen in a very near future in view of the unstable nature of ^{147}Gd ($t_{1/2} \approx 38$ h). An analysis of the sensitivity of P to this rate has been conducted by Rayet & Arnould (1992) for SN1987A.

In view of the difficulty of predicting P reliably, one has to conclude that ^{146}Sm cannot be viewed at this point as a reliable p-process chronometer.

3.1.3. ^{205}Pb: a short-lived s-process chronometer?

Among the short-lived radionuclides of potential cosmochemical and astrophysical interest, ^{205}Pb ($t_{1/2} = 1.5 \times 10^7$ yr) has the distinctive property of being of pure s-process nature, at least if the ^{204}Tl β-decay competes successfully with its neutron capture in stellar plasmas. This remarkable feature has not escaped Dave's attention, and he has pioneered with his collaborators the study of the chronometric virtues of the ^{205}Pb–^{205}Tl pair (Blake et al., 1973; Blake & Schramm, 1975).

This early work has led its authors to express some doubts about the possibility to rank ^{205}Pb as a reliable s-process clock. Apart from the fact that the level of the possible ^{205}Pb contamination of the early solar system was very poorly known (only an upper limit of about 9×10^{-5} being available for the

(^{205}Pb/^{204}Pb)$_0$ ratio (Huey & Kohman, 1972)), this pessimism related to the realization that electron captures by the thermally populated 2.3 keV first excited state of ^{205}Pb might reduce drastically the ^{205}Pb effective lifetime in a wide range of astrophysical conditions. Of course, the likelihood of a late injection of ^{205}Pb into the (proto-)solar nebula was reduced accordingly.

This conclusion has been demonstrated to be invalid, in certain s-process conditions at least. The ^{205}Pb destruction into ^{205}Tl by electron captures may indeed be efficiently hindered by the reverse transformation, which is made possible as a result of the ^{205}Tl bound-state β-decay. The nuclear aspects of this question have been analyzed in considerable detail by Yokoi et al. (1985), who have shown on grounds of schematic astrophysical models that the possible level of ^{205}Pb s-process production may be large enough to justify a renewed interest for the ^{205}Pb–^{205}Tl pair.

The work of Yokoi et al. (1985) has indeed triggered further observational, experimental and theoretical efforts. In particular, a new measurement of the (^{205}Pb/^{204}Pb)$_0$ ratio has been attempted, leading to a value of about 3×10^{-4} (Chen & Wasserburg, 1987). On the other hand, some experiments are currently deviced in order to obtain a direct measurement of the ^{205}Tl–^{205}Pb mass difference with high precision (Vanhorenbeeck, 1998). This quantity, which is still somewhat uncertain, affects quite drastically the predicted ^{205}Tl bound-state β-decay. Finally, more reliable estimates of the ^{205}Pb yields have been obtained through detailed s-process calculations performed with the help of realistic model stars. This concerns in particular Wolf-Rayet stars (see Section 3.1.1). Some estimates of the yields from thermally pulsing Asymptotic Giant Branch (AGB) stars have also been made (Wasserburg et al., 1994), with special emphasis on the ability of ^{205}Pb to survive in neutron-free locations in between thermal pulses (Mowlavi et al., 1998). The latter work concludes that the chances for a significant ^{205}Pb yield from AGB stars are likely to increase with the stellar mass for a given metallicity, or to increase with decreasing metallicity for a given stellar mass. However, the modelling of the s-process in AGB stars still raises many questions which remain to be answered before putting the ^{205}Pb yields from these stars on a safe footing.

In short, one may conclude from the above considerations that much cosmochemical, nuclear and astrophysics work remains to be done for giving a chance to ^{205}Pb to gain the status of a reliable short-lived s-process chronometer.

3.2. Extinct short-lived radionuclides in the solar system

The year 1987 has marked the tenth anniversary of the first discovery and isolation of presolar grains in meteorites. This has been the start of a remarkable series of dedicated laboratory work that has by now led to the identification and analysis of a long suite of such grains, interpreted as specks of stardust having survived the formation of the solar system. These presolar materials are refractories of various types (diamond, SiC, graphite, corrundum, silicon nitride), some of them containing even tiny subgrains, in particular, Ti-, Zr- and Mo-carbide or TiC subgrains in graphite or SiC grains, respectively (see Bernatowicz & Zinner (1997) for many contributions on presolar grains). All the analyzed elements contained in these grains exhibit much larger anomalies than those found in the material that condensed in the solar system itself. This is interpreted as the largely undiluted nucleosynthetic signature of specific stellar sources.

This rule applies in particular to the ^{26}Mg excesses attributed to the in situ decay of ^{26}Al observed in presolar silicon carbide, graphite and oxide grains, as demonstrated by e.g. Fig. 14 of MacPherson et al. (1995) (see also the reviews on specific grain types in Bernatowicz & Zinner, 1997). The initial ^{26}Al/^{27}Al ratio inferred to have been present in the analyzed grains vary from about 10^{-5} to values as high as about 0.5, to be compared to the canonical solar system value (^{26}Al/^{27}Al)$_0 \approx 5 \times 10^{-5}$ (Section 3.1.1). The highest reported ratios obviously put particularly drastic constraints on the ^{26}Al production models, especially when the Al data are complemented with correlated isotopic anomalies in other elements, and in particular in C, N, and O. As discussed in some detail by Arnould et al. (1997a), WR stars could well explain even the highest reported ^{26}Al/^{27}Al ratios, but might have some problem accounting for the isotopic composition of, in particular, nitrogen. In addition, one has to acknowledge that there is no clear indication at this point that the types of grains loaded with large ^{26}Al amounts can indeed condense from the WR winds.

Another example is provided by an extraordinary neon component, referred to as Ne-E(L), which is carried by presolar graphite grains, and is made of almost pure ^{22}Ne (e.g. Amari et al., 1995). This remarkable feature is generally interpreted in terms of the in situ decay of the ultra-short radionuclide ^{22}Na ($t_{1/2} \approx 2.6$ yr). In view of its short lifetime, the production of ^{22}Na in the thermonuclear framework requires the consideration of explosive situations. The first explicit connection of this sort has been made by Arnould & Beelen (1974) through detailed explosive H burning calculations. They substantiated the later view (Clayton & Hoyle, 1976) that Ne-E is hosted by nova grains[5]. Over the years, many calculations have been carried out along these lines (e.g. Jose (1998) for a recent study). Supernovae could also be ^{22}Na producers through explosive C burning, as demonstrated by the early calculations of Arnett & Wefel (1978), and confirmed by more recent studies (e.g. Woosley & Weaver, 1995).

Some graphite grains and a couple of special SiC grains (referred to as SiC-X) also carry ^{41}K excesses of up to two times solar that are attributed to the in situ decay of ^{41}Ca ($t_{1/2} = 10^5$ yr). From these observations, the intial ^{41}Ca abundances are inferred to lie in the $10^{-3} \lesssim {}^{41}\mathrm{Ca}/{}^{40}\mathrm{Ca} \lesssim 10^{-2}$ range (Amari & Zinner, 1997). The ^{41}Ca production may be due to a s-process-type of neutron captures associated with He burning in AGB (Wasserburg et al., 1995) or in WR (Arnould et al., 1997a) stars. However, the (uncertain) ^{41}Ca load of the AGB winds is predicted to be too low to account for the observations. The situation is slightly more favorable in the case of the WR stars, even if the highest observed ratios remain out of reach. Supernovae can also eject some ^{41}Ca whose abundance relative to ^{40}Ca can be of the order of 10^{-2} in a variety of O- and C-rich layers (Woosley & Weaver, 1995). A suite of isotopic anomalies accompanies the ^{41}K excess, and in particular an inferred ^{26}Al/^{27}Al ratio ranging typically between 0.01 and 0.1. Accounting for these correlated anomalies may be a source of embarassment for the supernova scenario. Their proponents call in particular for some large scale mixing of various and ad hoc amounts of different supernova layers.

Finally, evidence for the presence of ^{44}Ti ($t_{1/2} \approx 60$ yr) in some graphite and SiC-X grains is provided by ^{44}Ca excesses that translate into ^{44}Ca/^{40}Ca ratios of up to about 140 times solar (Amari & Zinner, 1997). This radionuclide is predicted to be produced in the so-called α-rich freeze-out developing in the layers of a Type II supernova located just outside the forming neutron star. The corresponding yields are thus extremely sensitive to the still uncertain details of the physics of the explosion. It might also be produced in some Type Ia supernova models where He detonation plays an important role (e.g. Woosley & Weaver (1995), and references therein). The isotopic anomalies that correlate with the ^{44}Ca excess are generally considered to demonstrate a Type II supernova origin of the carrier grains (Nittler et al., 1996). Again, a large mixing of ad hoc amounts of different supernova layers has to be postulated. The possibility of getting just the right mixing of course remains to be demonstrated.

4. Gamma-ray lines from cosmic radioactivities

As reviewed in the previous sections, short- or ultra-short-lived radionuclides have left their signatures in solar system solids or meteoritic presolar grains in the form of excesses of their daughter products. They may also be identifiable in the present interstellar medium if their decay leads to a substantial feeding of a nuclear excited state of the daughter products. In such a situation, their electromagnetic de-excitation produces γ-ray lines with specific energies, usually in the MeV domain.

Gamma-ray astrophysics complements in a very important way the study of extinct radionuclides in

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[5] The two forms of Ne-E identified nowadays, Ne-E(L) and Ne-E(H), were not known at that time. It is generally considered by now that the less extreme ^{22}Ne enrichments exhibited by Ne-E(H) do not require a ^{22}Na-decay origin.

meteorites. In particular, it provides information on the present-day production of these nuclides; it also allows in some instances a direct identification of their nucleosynthetic sources, while the cosmochemical inferences are necessarily indirect. In spite of this complementarity, γ-ray astrophysics is one of the rare astrophysical disciplines that escaped Dave's interest. Clayton and his collaborators pioneered the study of the detectability of γ-ray lines from the decay of radioactive nuclei synthesized in supernova explosions, about 30 years ago. This research was in fact the natural follow-up of the predictions (Bodansky et al., 1965) that ^{56}Fe is produced in a supernova as the radioactive ^{56}Ni, its ^{56}Co decay product ($t_{1/2} \approx 77$ days) being in its turn responsible for the powering of the optical supernova light curves. This early work has been followed by the prediction that additional radionuclides could be detectable as γ-ray line emitters (e.g. Clayton, 1982). With time, it has also been realized that supernovae are not the sole objects of relevance in this field, and that various radionuclides could also be ejected from novae, or even mass-losing AGB or WR stars.

On the observational side, γ-ray line astronomy has received considerable momentum in the 80ies with the detection of ^{26}Al in the Milky Way and of ^{56}Co in the supernova SN1987A. In the early 90ies, the Compton Gamma-Ray Observatory (CGRO, with the OSSE and COMPTEL instruments in particular) has contributed further to promote γ-ray line astronomy to a mature astrophysical discipline (see Diehl & Timmes (1998), Prantzos (1999) for recent reviews).

4.1. Basics of γ-ray line astronomy

The most important radioactivities for γ-ray line astronomy are presented in Table 1, along with the corresponding lifetimes, energies, branching ratios, main processes of production, and sites where γ-ray lines have been, or are expected to be, detected. It is seen that many of the nuclides of cosmochemical interest discussed in the previous sections (^{22}Na, ^{26}Al, ^{44}Ti and ^{60}Fe) are also γ-ray line radioactivities.

The production of a radionuclide at a high enough level and its decay to an excited state of its daughter nucleus are necessary but not sufficient conditions

Table 1
Cosmic radioactivities and γ-ray lines

Decay chain	Lifetime [a] (yr)	Line energies (MeV)	Site [detected]	Main process
$^{56}\mathrm{Ni} \rightarrow {}^{56}\mathrm{Co} \rightarrow {}^{56}\mathrm{Fe}$	0.31	$\underline{0.847}$ (1) $\underline{1.238}$ (0.685) 2.598 (0.17) 1.771 (0.45)	SN [SN1987A] [SN1991T]	NSE
$^{57}\mathrm{Co} \rightarrow {}^{57}\mathrm{Fe}$	1.1	$\underline{0.122}$ (0.86) $\underline{0.136}$ (0.11)	SN [SN1987A]	α-NSE
$^{22}\mathrm{Na} \rightarrow {}^{22}\mathrm{Ne}$	3.8	1.275 (1)	novae	Ex H
$^{44}\mathrm{Ti} \rightarrow {}^{44}\mathrm{Sc} \rightarrow {}^{44}\mathrm{Ca}$	90	$\underline{1.156}$(1) 0.068 (1) 0.078 (0.98)	SN [CasA, GRO J0852-4642]	α-NSE
$^{26}\mathrm{Al} \rightarrow {}^{26}\mathrm{Mg}$	1.1×10^6	$\underline{1.809}$ (1)	WR, AGB novae SNII [Galaxy]	St H Ex H St + Ex Ne
$^{60}\mathrm{Fe} \rightarrow {}^{60}\mathrm{Co} \rightarrow {}^{60}\mathrm{Ni}$	2.2×10^6	1.322 (1) 1.173(1)	SN	n-NSE

[a] For double decay chains the longest lifetime is given; *underlined*: lines already detected; Numbers in *parentheses*: branching ratios; In *brackets*: sites of line detection; SN: supernova; SNII: Type II supernova; St: Hydrostatic burning; Ex: Explosive burning; NSE: Nuclear statistical equilibrium; α: α-rich freeze-out; n-: normal freeze-out.

for it to be an interesting candidate for γ-ray astronomy. Other factors indeed play a key role. This concerns in particular the decay lifetimes, which enter the problem through the fact that the production of the nuclei of interest takes place in environments initially opaque to γ-rays; these photons are thus degraded in energy as they interact with the surrounding material. The γ-ray lines have in fact a significant probability to be detectable only if the matter densities, and thus the opacities, become low enough on timescales shorter than the radioactive decay lifetimes. These conditions can be met in AGB or WR stars, which eject through extensive steady winds a substantial fraction of their relatively low-density outer material that can be enriched with certain γ-ray line candidates. However, most radionuclides of interest are produced in explosive events of the nova or supernova types. In the latter case the synthesis of the nuclides of relevance takes place in highly opaque deep layers, so that especially drastic constraints are put on the γ-ray line observability. The situation is, in fact, quite different when dealing with the low-mass star explosions (Type Ia supernovae, SNIa), or with explosions of massive stars (Type II supernovae, SNII). The SNIa ejecta reach low opacites much more quickly than the SNII ones in view of their lower masses ($\sim 1\,M_\odot$) and larger ejection velocities (in excess of 1.5×10^4 km/s). More specifically, the ejecta become transparent to γ-ray photons typically after a few weeks in SNIa and only after about one year in the SNII case. Even if SNIa provide better detection conditions, they forbid in particular the observation of the γ-ray line associated with the decay of the important nuclide ^{56}Ni, whose half-life is only 6 days.

The intensity of the escaping γ-ray lines gives important information on the yields of the decaying nuclides and on the physical conditions (temperature, density, neutron excess, etc.) in their production zones. In addition, the shape of the γ-ray lines reflects the velocity distribution of the ejecta, and can thus help probing its structure (e.g. Burrows, 1991). Up to now, only the ^{56}Co lines from SN1987A and the ^{26}Al line from the inner Galaxy have been resolved.

When the lifetime of a radionuclide is not much larger than the time interval between two nucleosynthetic events in the Galaxy, those events appear as γ-ray point sources. In the opposite case, a diffuse galactic emission is expected from the integrated emission of many sources. Characteristic timescales between two explosions are about 1 to 2 weeks for novae, about 40 yr for SNII + SNIb, and about 300 yr for SNIa, these values being derived from the galactic frequencies of the corresponding events (Della Vale & Livio, 1994; Tammann et al., 1994). A comparison between these timescales and the decay lifetimes of Table 1 indicates that ^{26}Al and ^{60}Fe must be responsible for a diffuse emission, the spatial distribution of which reflects the galactic distribution of the nucleosynthetic sources (except if high velocity ejecta can travel undecelerated for long times; see Section 4.4). The other radioactivities of Table 1 should be seen as point sources in the Galaxy, except perhaps ^{22}Na if it is dominantly produced by ONeMg-rich novae. Indeed, about 40 of these objects might explode in the Galaxy over the ^{22}Na lifetime.

4.2. *^{56}Co and ^{57}Co lines from supernovae*

The observations in SN1987A of γ-ray lines associated with the ^{56}Co and ^{57}Co decays have confirmed in a spectacular way the predictions concerning the synthesis of radioactive nuclei in supernovae. In particular, they have demonstrated that ^{56}Fe, the most strongly bound stable nucleus in nature is produced in the form of unstable ^{56}Ni. The main points of relevance to γ-ray-line astronomy are as follows:

1. The detection of the 0.847 and 1.238 MeV ^{56}Fe de-excitation lines (Matz et al., 1988) about 6 months earlier than expected suggests that the SN1987A ejecta has suffered large scale mixing and/or fragmentation during the explosion or shortly after, bringing heavy nuclei from the inner layers into the outer ones. This implies that the explosion does not preserve the onion-skin structure predicted by 1-D pre-supernova model stars. Prompted by this observation, hydrodynamical 2-D and 3-D simulations showed that mixing may indeed take place, due mostly to Rayleigh-Taylor type instabilities (e.g. Fryxel et al., 1991; Hashisu et al., 1990). This was a major contribution of

γ-ray line astronomy to the understanding of supernova explosions;

2. The observed profiles of the 0.847 and 1.238 MeV lines are red-shifted by 500–800 $\mathrm{km\,s^{-1}}$ (Tueller et al., 1990). This is at variance with the expectations based on the hypothesis of an optically thick source. In addition, their width is larger than predicted from theory, probably indicating that some fraction of ^{56}Co has penetrated deeply into the high-velocity H-rich envelope. Despite some preliminary models (Burrows & van Riper, 1995; Grant & Dean, 1993), a convincing explanation of these data does not exist yet;
3. The features discovered at 122 and 136 keV (Kurfess et al., 1992) are associated to the decay of ^{57}Co. From the line intensities, the mass of ^{57}Co is estimated to be about $2.7\times10^{-3}\,M_{\odot}$, which implies a ^{57}Ni/^{56}Ni production ratio of 1.40 ± 0.35 times the solar ratio $(^{57}\mathrm{Fe}/^{56}\mathrm{Fe})_{\odot}$ of the stable daughter nuclei. This suggests that most of the ^{57}Co has been produced in an "α-rich" freeze-out characteristic of a relatively low-density environment (Clayton et al., 1992). The ^{57}Co amount derived in such a way is compatible with the one needed to account for the latest measured UVBRIJHK light curves of SN1987A (Fransson & Kozma, 1998).

It has to be noted that the ^{56}Co and ^{57}Co line observations reported above have been made possible because of the proximity of SN1987A. In fact, these lines would have remained undetected with the available instruments if the same event had occurred in the Andromeda galaxy, and they would have been just marginally detectable by an INTEGRAL-type instrument (to be launched in 2001). This is due to the long timescale required for the slowly expanding massive ejecta of SN1987A (of the SNII type) to become transparent to γ-rays. As discussed in Section 4.1, this attenuation would have been much less drastic in a SNIa case. An additional factor in favour of SNIa is that these explosions are predicted to produce about 0.5 to $1\,M_{\odot}$ of ^{56}Ni, which is typically ten times the average SNII yield. In such conditions, the ^{56}Co lines from SNIa would be detectable up to the Virgo cluster of galaxies (located at about 13–20 Mpc) by instruments with a sensitivity of about $10^{-5}\,\mathrm{cm^{-2}\,s^{-1}}$, which is close to the sensitivity limit of CGRO.

Evidence for the 847 and 1238 keV ^{56}Co lines has been obtained by COMPTEL 66 and 176 days after the explosion of the bright SNIa SN1991T in the spiral galaxy NGC4527, which is located at an estimated distance of 17 Mpc at the periphery of the Virgo cluster. The obtained line flux (Morris et al., 1995) corresponds to more than $1.3\,M_{\odot}$ of ^{56}Ni if the distance exceeds 13 Mpc, implying that almost the entire exploding white dwarf responsible for the supernova has been incinerated into ^{56}Ni. Sub-Chandrasekhar mass models for SNIa (with a detonation at the base of the accreted He layer inducing a further detonation inside the white dwarf), or delayed detonation models (where the flame front propagates subsonically at large distances from the centre of the white dwarf before turning into a detonation) may explain an early detection of the γ-ray lines. However, they may have problems accounting for the reported large ^{56}Ni amounts. Before drawing firmer conclusions, further detections of extragalactic SNIa are required, particularly in order to clarify if indeed SN1991T can be considered as typical.

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 performed recently (Gomez-Gomar et al., 1998; Höfflich et al., 1998). However, a statistical analysis shows that the prospect of detecting SNIa with INTEGRAL is rather dim, since its sensitivity to broad lines, such as those expected from the high velocity SNIa ejecta, is not much better than the CGRO one (for recent estimates, see Timmes & Woosley, 1997).

4.3. *^{44}Ti lines from supernovae*

As the ^{44}Ti lifetime (~ 60 yr) is comparable to the characteristic timescale between two supernova explosions in the Milky Way, the resulting γ-ray line emission should appear as point sources. On the other hand, this lifetime is sufficiently long for making ^{44}Ti an excellent probe of galactic supernova explosions in the past few centuries. In fact, its γ-ray lines might reveal supernova remnants (SNR) which have remained undetected up to now at other wavelengths. This has been demonstrated by the recent detection of a 1.16 MeV emission from the previously unknown and presumably nearby SNR GRO J0852-4642 (Iyudin et al., 1998).

Cas A is one of the youngest (about 340 yr old) and closest (about 3 kpc) known supernova remnants. Optical and X-ray measurements suggest that its progenitor was a $20\,M_\odot$ WR star that exploded as an underluminous supernova of the SNIb type. This could explain why the explosion has remained undetected, despite its proximity and high declination. The 1.16 MeV ^{44}Ti line has been detected in this remnant by COMPTEL with a flux of $(4.2\pm0.9)\times10^{-5}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ (Iyudin et al., 1997). This translates into a ^{44}Ti yield of about $1.5\times10^{-4}\,M_\odot$, which is not too far from the theoretical predictions. However, this detection has brought forward an unexpected puzzle. Since ^{44}Ti and ^{56}Ni are synthesized in the same stellar zones, the inferred amount of ^{44}Ti has to be accompanied by about $0.05\,M_\odot$ of ^{56}Ni. If powered by the ^{56}Ni decay, the supernova (with or without a hydrogen envelope) would have a peak magnitude $M_V < -4$ at 3 kpc (The et al., 1995). This implies that Cas A should have been a rather bright supernova for a few weeks, making it difficult to understand why it went unreported. Among the various proposed solutions to the puzzle, the hiding of Cas A by a dusty shell made of wind-ejected pre-supernova material appears as a natural explanation, especially if the progenitor was a WR star (Hartmann et al., 1997). Another interesting possibility is that the decay rate of ^{44}Ti was reduced during the early evolution of the Cas A remnant (^{44}Ti decays by orbital electron capture and few bound electrons exist in an ionised environment). In that case, the initial ^{44}Ti mass may have been lower than implied by its currently observed activity (Mochizuki et al., 1999).

Note that ^{44}Ti is the third radioactivity that will eventually be discovered in SN1987A. Along with ^{57}Co it is produced in the hottest and deepest layers expelled by a SNII, so that the ^{44}Ti and ^{57}Co yields are very sensitive to the poorly understood physics of the explosion, and in particular to the position of the ‘‘mass-cut’’ (i.e. the line dividing the supernova ejecta from the matter accreted onto the compact residue). Nucleosynthesis calculations for SN1987A predict the ejection of about $1.5\times10^{-4}\,M_\odot$ of ^{44}Ti (e.g. Thielemann et al., 1996). Comparable amounts are suggested from the fitting of the late SN1987A light curve if it is indeed powered by ^{44}Ti (Fransson & Kozma, 1998). Such amounts of ^{44}Ti would produce on Earth a flux of about $3\times10^{-6}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ in the 68, 78 and 1157 keV lines for many decades after the explosion. If ^{44}Ti is ejected at low speed (around 10^3 km/s, as suggested by spherically symmetric models for SN1987A), the kinetic broadening of the lines has to be small, and the estimated fluxes would be close to the sensitivity limit of INTEGRAL for narrow lines. The detection of ^{44}Ti from SN1987A will certainly be a prime target for that satellite, as it will provide a better probe than ever of the deepest layers ejected by SN1987A.

4.4. ^{26}Al *and* ^{60}Fe *(?) in the galactic plane*

The detection by HEAO-3 of the 1.8 MeV line associated with the decay of ^{26}Al (Mahoney et al., 1982) has marked the birth of the astrophysics of γ-ray lines. This observation provides an additional demonstration that nucleosynthesis is currently active in the Galaxy, and offers an interesting opportunity to identify one of the sites of that activity (see Prantzos & Diehl (1996) for a review of the ^{26}Al γ-ray line astronomy and synthesis models).

The COMPTEL ^{26}Al data reviewed by Diehl et al. (1999) clearly exhibit a diffuse and irregular 1.8 MeV flux along the galactic plane (Fig. 2). These features provide an especially good tracer of the current galactic ^{26}Al production sites. In particular, they exclude (i) a unique point source in the galactic centre, (ii) a strong contribution from the old stellar population of the galactic bulge, 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. In contrast, they favour massive stars as the production sites for (most of) the derived amount (about $2.5\,M_\odot$) of galactic ^{26}Al (e.g. Prantzos, 1993). This scenario is made plausible in particular by the observed 1.8 MeV ‘‘hotspots’’ with tangents to the spiral arms (Diehl et al., 1995)[6]. An additional support comes from the high level of similarity between a galactic

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[6] Note, however, that two of the COMPTEL 1.8 MeV hotspots located at the approximate galactic longitudes of 80° and 90° are certainly not related to spiral features (Cygnus superbubble, Vela region). In addition, the 1.8 MeV Vela hotspot is not associated with the nearby Vela supernova remnant alone, as originally thought (Diehl et al., 1999).

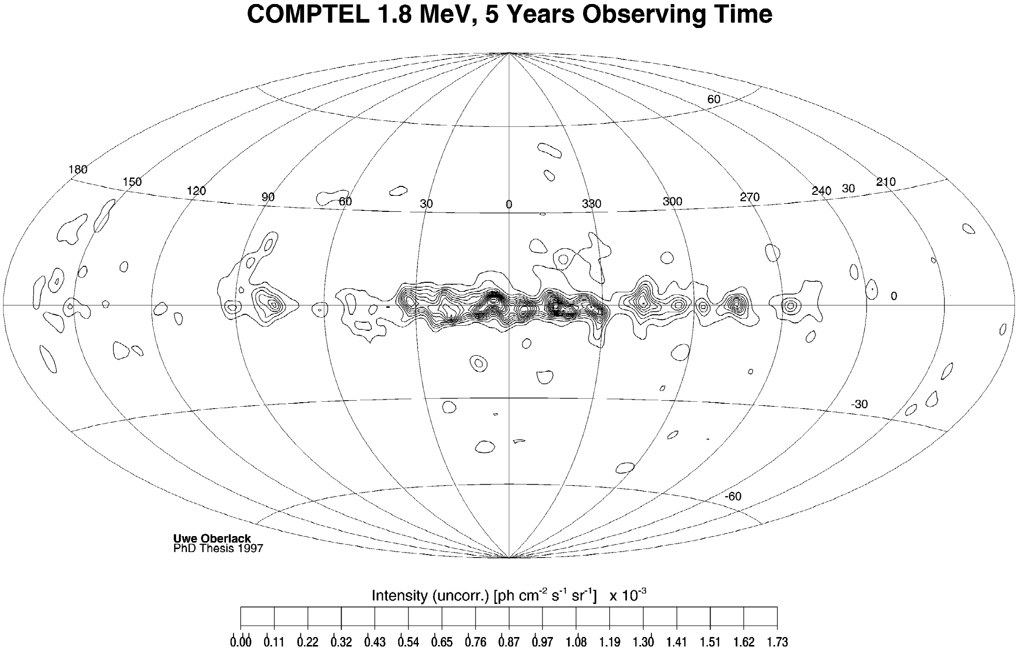

Fig. 2. Map of the Galaxy in the light of the 1.8 MeV line of ^{26}Al (COMPTEL team).

map of the ionisation power from massive stars and the 1.8 MeV map of the galactic ^{26}Al. From these similar maps and the choice of a standard initial mass function (Knödlseder, 1999) is able to reproduce the current galactic supernova rate and massive star population, and suggests that most of the ^{26}Al is produced by high metallicity WR stars in the inner Galaxy.

An intriguing recent observation concerns the spectral width of the 1.8 MeV line from the inner Galaxy, which is estimated from measurements by the GRIS spectrometer (Naya et al., 1996) to be $\Delta E = 5.4 \pm 1.4$ keV. This is larger than the value of about 1 keV expected from the galactic rotation. Even if ^{26}Al is initially ejected at high velocities, it is difficult to understand how it could go undecelarated during most of its 1 My lifetime. Among the possibilities explored by Chen et al. (1997), the condensation of ^{26}Al in high-speed dust grains seems promising. However, the GRIS measurement needs to be confirmed in the first place, since it is incompatible with the HEAO C line width limit of 3 keV.

An exciting perspective for INTEGRAL is the possibility to detect a diffuse γ-ray emission at 1.2 and 1.3 MeV associated with the decay of ^{60}Fe, and give some hints about its distribution in the Galaxy. Indeed, the SNII models of Woosley & Weaver (1995) predict a ^{60}Fe to ^{26}Al yield ratio of about 0.25-0.35 when averaged over a reasonable stellar initial mass function. Taking into account the respective ^{60}Fe and ^{26}Al lifetimes (Table 1), the ^{60}Fe line flux is expected to be about 0.15 times lower than the ^{26}Al one if indeed SNII are the major galactic ^{26}Al producers. If INTEGRAL is unable to detect the ^{60}Fe lines, SNII might have to be discarded as major ^{26}Al sources. At this point, it may be of interest to emphasize that the ^{60}Fe SNII yields depend upon the details of the explosion model, and are thus still uncertain. On the other hand, WR stars are also ^{26}Al and ^{60}Fe producers during their non-explosive and explosive (SNIb/c) phases, respectively. This might complicate the interpretation of a possible ^{60}Fe detection by INTEGRAL.

5. Summary and perspectives

The decay of a variety of nuclides recorded in live or fossil form in the solar system brings a rich variety of information about a vast diversity of highly interesting astrophysical questions. Dave Schramm has written important pages of many chapters of this ‘‘astrophysics of cosmic radioactivities’’ with his incomparable dynamism and visionary perception of astrophysics. He has without doubt triggered much work in the field and shown many new ways. For sure, he would be most gratified to know that so much remains to be done and said, and that each day brings its share of renewed excitement and laboratory discoveries.

Gamma-ray line astronomy has become rightly one of the important components on the scene, complementing nicely the information on cosmic radioactivities gained from cosmochemical studies. The already observed γ-ray lines from ^{56}Co, ^{57}Co, ^{44}Ti and ^{26}Al have allowed to probe various interesting aspects of supernova explosions, and to better define the level of success, and also of failure, of simple supernova models. The ^{26}Al emission line has also helped locating sites of active large scale nucleosynthesis in the Galaxy. The future of this young astronomy is bright, with the much awaited launch of INTEGRAL, a γ-telescope with improved sensitivity, to be launched be ESA by the year 2001. In Table 2 we present a brief synopsis of some stellar nucleosynthesis problems that could be tackled with that instrument.

Table 2
Some prospects for stellar γ-ray lines with INTEGRAL

Isotope	Line E (MeV)	Target	Observable	Interest
^{56}Co	0.847	extragalactic	intensity	constrain models
	1.238	SNIa	shape	of SNIa
		SN1987A	flux	nucleosynthesis
				mass-cut
	0.068			
^{44}Ti	0.078	CasA	confirmation	$v_{ej}^{a} \rightarrow$ CasA age
	1.156		+ shape	+ models
		Galactic SN	intensity	models +
			+ shape	nucleosynthesis
		Galaxy	accurate map	nucleosynthesis sites
			line width	ejecta propagation
^{26}Al	1.809			
		Galactic	line shape	distances
		hotspots	flux	yields
		(e.g. Vela)	extent	v_{ej}^{a}
^{56}Fe	1.173	Galaxy	flux	sources
	1.322		(map?)	
^{22}Na	1.275	novae	flux, shape	models

[a] v_{ej}: speed of SN ejecta.

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