Some selected comments on cosmic radioactivities

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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 Jerry Wasserburg.

First, the virtues of the long-lived (half-lives $t_{1/2}$ close to, or in excess of $10^9$ y) radionuclides as galactic chronometers are discussed in the light of recent observational and theoretical works. It is concluded that the trans-actinide clocks based on the solar system abundances of $^{232}$Th, $^{235}$U and $^{238}$U or on the $^{232}$Th surface content of some old stars are still unable to meaningfully complement galactic age estimates derived from other independent astrophysical methods. In this respect, there is reasonable hope that the $^{187}$Re-$^{187}$Os chronometric pair could offer better prospects. The special case of $^{176}$Lu, which is a pure s-process product, is also reviewed. It is generally considered today that this radionuclide cannot be viewed as a reliable s-process chronometer.

Second, we comment on the astrophysical messages that could be brought by short-lived ($10^5 < t_{1/2} < 10^8$ y) radionuclides that have been present in live or in fossil form in the early solar system. From an astrophysical point of view, the demonstrated early existence of live short-lived radionuclides is generally considered to provide the most sensitive radiometric probe concerning discrete nucleosynthetic events that presumably contaminated the solar system at times between about $10^5$ and $10^8$ y prior to the isolation of the solar material from the general galactic material. Of course, this assumes implicitly that the radionuclides of interest have not been synthesized in the solar system itself. This is still a matter of debate, as we briefly stress. If indeed the short-lived radionuclides that have been present live in the early solar system are not of local origin, the external contaminating agents that have been envisioned are supernovae, evolved stars of the Asymptotic Giant Branch (AGB) type, or massive mass-losing stars of the Wolf-Rayet (WR) type. We comment on some aspects of the AGB or WR contamination. In the latter case, we discuss more specifically the role of...
rotation and of binarity on the predicted yields of $^{26}$Al, a radionuclide of special cosmochemistry and astrophysics interest. Some comments are also devoted to $^{146}$Sm and $^{205}$Pb. The former one is a short-lived p-process radionuclide that has most probably been in live form in the solar system, while the latter one is of s-process origin. It is shown to raise interesting nuclear physics and astrophysics questions, and to deserve further cosmochemical studies in order to evaluate its probability of existence in live form in the early solar system.

Third, the case of extinct short-lived radioactivities carried by pre-solar grains is shortly mentioned, and some comments are made about the possible origin of these grains.

Finally, a brief mention is made to $\gamma$-ray line astrophysics, which provides interesting information on live short-lived radionuclides in the present interstellar medium, and thus complements in a very important way the study of extinct radionuclides in meteorites. This is illustrated with the case of $^{26}$Al.

*Keywords:* Cosmochronology – Isotope ratios – Meteorites – Radioactive isotopes – Solar nebula
1. Introduction

Since its discovery about one century ago, nuclear radioactivity has been the focal point of a vast amount of fundamental and applied research. With time, it has become clearer and clearer that some radionuclides even try to tell us something quite exciting about certain facets of the Universe in general, and about our solar system in particular. With his legendary enthusiasm and expertise, Jerry Wasserburg has searched without respite for the Rosetta Stone leading to the understanding of the highly complex hieroglyphic message delivered by radionuclides to astrophysicists and cosmochemists. This contribution is a tribute to this aspect of Jerry’s multiple activities. 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 $\gamma$-ray domain. The study of these radionuclides offers invaluable information on their production sites and is the subject of $\gamma$-ray line astronomy, a recently developed astrophysical discipline which has not escaped Jerry’s intellectual curiosity.

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). 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 in determining $T_U$, as well as, to some extent at least, $T_{GC}$ and $T_{disc}$ (e.g. Fowler & Meisel 1986, Tayler 1986, Clayton 1988, Arnould & Takahashi 1990a). The $T_{GC}$ or $T_{disc}$ values have also been evaluated from the use of the Herzsprung-Russell diagram (HRD) (e.g. Jimenez 1998, VandenBerg et al. 1997 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 privileged $T_{disc}$ evaluator (e.g. Winget et al. 1987, 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). The age estimates they provide are sketched in a synopsis form in Fig. 1, which also displays the limits derived from the nucleo-cosmochronological approach briefly discussed below.
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 $T_{\text{nucl}}$ of the nuclides in the galactic disc through the use of the observed bulk (meteoritic) abundances of radionuclides with lifetimes commensurable with presumed $T_{\text{disc}}$ values (referred to in the following as ‘long-lived’ radionuclides). Consequently, it is hoped to provide at least a lower limit to $T_{\text{disc}}$. The most studied chronometries involve $^{187}\text{Re}$ or the trans-actinides $^{232}\text{Th}$, $^{235}\text{U}$ and $^{238}\text{U}$.

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.

The trans-actinide clocks  The familiar long-lived $^{232}\text{Th}$-$^{238}\text{U}$ and $^{235}\text{U}$-$^{238}\text{U}$ chronometric pairs (Fowler & Hoyle 1960) are developed on grounds of their abundances at the time of solidification in the solar system some $4.56 \times 10^9$ y 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. 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 $^{209}\text{Bi}$, 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. This difficulty is illustrated by the recent calculations of Goriely & Clerbaux (1999). One has to note, however, that many authors express opposite views on this question (e.g. Pfeiffer et al. 1998). An additional problem the trans-actinide clocks has to face relates to the fact that most of the r-process precursors of U and Th are unknown in the laboratory, and will remain so for a long time to come. Theoretical predictions of properties of interest, like masses, $\beta$-decay strength functions and fission barriers, are extremely difficult,
particularly as relevant calibrating data are largely missing. The problems mentioned above 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 with little consideration of the chemical evolution in the solar neighborhood. 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). 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 (ISM) by the stars at their birth (e.g. Yokoi et al. 1983). However, Jerry, in collaboration with Schramm (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 $9 \lesssim T_{\text{nuc}} \lesssim 27$ Gy (Meyer & Schramm 1986).

There has also been an attempt to develop a Th-chronometry (e.g. Pagel 1997) 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 a variety of stars with metallicities in a wide range of values (da Silva et al. 1990, François et al. 1993). 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 to time through a chemical evolution model (e.g. Pagel 1997). This is by far not a trivial matter. One of the difficulties noted by François et al. (1993) arises from the complex trend of the observed Th/Eu abundance data with metallicity. The Th observations in highly metal-deficient stars (e.g. Sneden et al. 1998, and references therein) alleviate the difficulties inherent in the chemical evolution models. The considered stars have indeed been born in the Galaxy at times much shorter than the Th decay half-life. As a consequence, Th could not have been affected by chemical evolution effects, and only a simple exponential decay law has to be applied. This does not imply, however, that $T_{\text{nuc}}$ can be trivially derived from these observations. One of the main problems again concerns the assumption that the Th/Eu production ratio is strictly solar in all r-process

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1Originally, 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
sites. There is at best some hint that this could indeed be the case (Sneden et al. 1998), but, in our opinion, it would be premature to interpret this hint as a demonstration.

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 favorable 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 derived ages).

The $^{187}\text{Re} - {^{187}\text{Os}}$ chronometry First introduced by Clayton (1964), the chronometry using the $^{187}\text{Re}-^{187}\text{Os}$ pair is able to avoid the difficulties related to the r-process modeling. True, $^{187}\text{Re}$ is an r-nuclide. However, $^{187}\text{Os}$ is not produced directly by the r-process, but indirectly via the $\beta^-$-decay of $^{187}\text{Re}$ ($t_{1/2} \approx 43$ Gy) over the galactic lifetime. This makes it in principle possible to derive a lower bound for $T_{\text{nuc}}$ from the mother-daughter abundance ratio, provided that the ‘cosmogenic’ $^{187}\text{Os}$ 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 $^{187}\text{Os}$ s-process component from the ratio of its production to the one of the s-only nuclide $^{186}\text{Os}$ 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 $^{187}\text{Os}$ 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 for a departure from the steady-flow predictions for the $^{187}\text{Os}/^{186}\text{Os}$ production ratio (e.g. Arnould et al. 1984, Käppeler et al. 1991); and 2) at the high temperatures, and thus high ionisation states, $^{187}\text{Re}$ may experience in stellar interiors, its $\beta^-$-decay rate may be considerably, and sometimes enormously, enhanced over the laboratory value by the bound-state $\beta^-$-decay of its ground state to the 9.75 keV excited state of $^{187}\text{Os}$ (e.g. Yokoi et al. 1983). Such an enhancement has recently been beautifully confirmed by the measurement of the decay of fully-ionised $^{187}\text{Re}$ at the
The inverse transformation of $^{187}\text{Os}$ via free-electron captures is certainly responsible for additional corrections to the stellar $^{187}\text{Re}/^{187}\text{Os}$ 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 detailed evolution models for $1 \lesssim M \lesssim 50 \, M_\odot$ stars and of a galactic chemical evolution model that is constrained by as many observational data in the solar neighborhood as possible in order to reduce as much as possible the uncertainties that are inherently associated with any model of this type (Takahashi 1998, Takahashi et al. 1998). This work, which is an update of Yokoi et al. (1983) with regards to meteoritic abundances, nuclear input data, stellar evolution models and observational constraints, concludes that $T_{\text{nuc}} \approx 15 \pm 3$ Gy. Even lower ages of about 9 Gy, as derived from the model-independent approach (Schramm 1990, Schramm & Wasserburg 1970; see Sect. 2.1), cannot conclusively be excluded within the remaining uncertainties in the chemical evolution model parameters.

These results may imply that the $^{187}\text{Re} - ^{187}\text{Os}$ 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 $T_{\text{nuc}}$ in a near future, and independently of other methods which suffer from problems of other types.

$^{176}\text{Lu}$, a long-lived s-process radionuclide The long-lived $^{176}\text{Lu}$ ($t_{1/2} = 41$ Gy) has the remarkable property of being shielded from the r-process, and thus to be a pure s-process product. Some early works (Arnould 1973, Audouze et al. 1972) have proposed this radionuclide to be a potential chronometer for the s-process, the other long-lived radionuclides probing the r-process instead. These studies pointed out some possible uncertainties in the solar $^{176}\text{Lu}$ 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 $^{176}\text{Lu}^m$ isomeric state. More specifically, the two different paths $^{175}\text{Lu}^g(n, \gamma)_{^{176}\text{Lu}^g}^{177}\text{Hf}$ and $^{175}\text{Lu}^m(n, \gamma)_{^{176}\text{Lu}^m}^{177}\text{Hf}$ may well develop during a s-process ($^{176}\text{Lu}^g$ designates the $^{176}\text{Lu}$ ground state). The resulting $^{176}\text{Lu}^g/^{176}\text{Hf}$ production ratios depend on the relative importance of these two branchings, and thus mainly on the relative population of the ground and isomeric $^{176}\text{Lu}$ states. Two limiting situations are relatively simple to handle. The first one is obtained if $^{176}\text{Lu}^g$ and $^{176}\text{Lu}^m$ 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 $^{175}\text{Lu}^g/n, \gamma)_{^{176}\text{Lu}^g}^{177}\text{Hf} / {^{175}\text{Lu}^m/n, \gamma)_{^{176}\text{Lu}^m}^{177}\text{Hf}$ cross section ratio, the value of which can be obtained from experiments. The other extreme is obtained if $^{176}\text{Lu}^g$ and $^{176}\text{Lu}^m$ 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 condi-
tions, 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 et al. 1991, Doll et al. 1999, and references therein). From these efforts, it is generally concluded today that the $^{176}$Lu s-process yields are so sensitive to temperatures and neutron densities that they cannot be evaluated precisely enough for chronological purposes. Instead, $^{176}$Lu 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 $10^5 \ll t_{1/2} \ll 10^8$ y 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 ($t_{1/2} = 2.6$ y) and $^{44}$Ti ($t_{1/2} \approx 60$ y; Wietfeldt 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, Jerry 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 $(^{26}$Al/$^{27}$Al)$_0$ ratio in the analyzed materials was ranging from well below

\footnote{Here and in the following, the subscript 0 refers to the start of solidification in the solar system some 4.56 Gy ago}
It is established by now that $^{26}$Al has been live in the solar system at a canonical level of $(^{26}\text{Al}/^{27}\text{Al})_0 \approx 5 \times 10^{-5}$ (MacPherson et al. 1995). Jerry and his collaborators have also contributed in a significant way to the accumulation of persuasive experimental evidence for the existence of other live radionuclides. This concerns nowadays $^{53}\text{Mn}$, $^{60}\text{Fe}$, $^{107}\text{Pd}$, $^{129}\text{I}$, $^{146}\text{Sm}$ and $^{244}\text{Pu}$. Other likely candidates are $^{182}\text{Hf}$ and $^{41}\text{Ca}$, the presence of which has recently been found to be correlated with the one of $^{26}\text{Al}$ in some primitive meteorites (Sahijpal et al. 1998). Some weaker evidence has been gathered about $^{36}\text{Cl}$, $^{92}\text{Nb}$, $^{99}\text{Tc}$ and $^{205}\text{Pb}$ (see e.g. Podosek & Nichols 1997 for a review and references).

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 $10^8$ y 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? This question has been revisited recently, as briefly mentioned in Sect. 4.

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. One form of such a ‘granular’ description is referred to as the ‘Bing Bang’ model (Reeves 1978, 1979), which envisions the contamination and formation of the solar system in an OB association during its approximate $10^7$ y 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.

It has to be emphasized that a Bing Bang type of model does not imply either a contamination by a single astrophysical source, or a strict relation between the contamination and the very formation of the solar system. In contrast, the possibility for

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$^{3}$OB associations are groupings of highly luminous and hot massive stars of the O and B spectral types. Many OB associations, which are about 30 to 200 parsec across (1 parsec is 3.26 lightyears), are made of smaller clusters of stars called OB subgroups containing about 5 to 20 stars, with an average of about 10. One of the best studied OB associations lies in the Orion cloud complex (e.g. Genzel & Stutzki 1989 for a review). OB associations are not bound by gravity. In addition, their constituting stars explode as supernovae after a rapid evolution not lasting more than a few tens of millions of years. As a consequence, these associations dissipate in a few times $10^7$ y. So, if the solar system had been born in an OB association, this star grouping would have disappeared a long time ago!
a given star to trigger the formation of the solar system and to contaminate it at the same time has received much attention over the years, and has recently been scrutinized within hydrodynamical models (e.g. Boss & Foster 1998, and references therein).

Supernovae, Asymptotic Giant Branch (AGB) or Wolf-Rayet (WR) stars have been identified as possible triggering/contaminating agents. They are briefly reviewed in Sects. 3.2 - 3.4. We also make some specific comments on the short-lived radionuclides $^{205}$Pb (Sect. 3.5) and $^{146}$Sm (Sect. 3.6) which have been explored by Jerry in some of his recent works.

3.2. Some brief comments on the supernova production of short-lived radionuclides

Supernova explosions are spectacular events representing the endpoint of the evolution of a variety of stars. Exploding massive ($M \gtrsim 10 \, M_\odot$) stars are classified as Type II supernovae (SNII) if hydrogen lines are present in their spectra. Some massive stars, and in particular Wolf-Rayet stars (see Sect. 3.4), may have lost their H envelope at the time of their explosion, which is generally classified as a Type Ib/c supernova (SNIb/c). Other supernovae, referred to as Type Ia (SNIa) are associated with the explosion of a compact star, referred to as a ‘white dwarf’, accreting material from a companion star in a binary system. The mechanism responsible for the SNIa is completely different from the one leading to SNII or SNIb/c.

Type II supernovae eject large amounts of nuclearly processed material into the interstellar medium, and could have injected live radionuclides into the solar system forming as a result of the explosion itself. Much has been written on the subject, and the reader is referred to e.g. Cameron et al. (1995) for details and further references. We just want to mention here that Jerry and his collaborators (Wasserburg et al. 1998) have proposed a test of the SNII trigger hypothesis based on the $^{56}$Fe/$^{56}$Fe ratio that would have to be found in $^{26}$Al-bearing samples if both radionuclides had just been produced by a SNII. Similar constraints could come from other stable or unstable nuclides that are predicted to be synthesized in the same SNII zones as the above-mentioned radionuclides, or in nearby regions. From the available experiments and predicted SNII yields, Wasserburg et al. (1998) note that the observed $^{56}$Fe abundances appear to be too low to be compatible with a supernova trigger that injected the $^{26}$Al into the protosolar nebula, the same conclusion also holding for $^{53}$Mn.

On the other hand, it has to be noticed that the SNII contaminating role might be enhanced by (isotopically anomalous) ‘shrapnel-like’ SN grains which have a higher penetration efficiency in the forming solar system than the gas from an expanding SN shell (Margolis 1979). In addition, such grains minimize the 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 required by the analysis of the isotopic anomalies attributed to the radionuclide in situ decay). The possible
role in the SN contamination efficiency of SN ‘fast moving knots’ stressed by Arnould & Nørgaard (1978) may be nicely complementary to the polluting importance of grains. There is indeed mounting evidence that fast moving knots are privileged locations of grain formation in SN 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.

Finally, let us note that other supernova types might also contribute to the synthesis of short-lived radionuclides. This is especially the case of SNIb/c which are often interpreted as exploding WR stars. This production (in particular of $^{53}$Mn, $^{60}$Fe or $^{146}$Sm) could complement the non-explosive WR contamination (see Sect. 3.4) after a time span that is shorter than the lifetime of the considered radionuclides.

3.3. Short-lived radionuclides from AGB stars

After their central hydrogen and helium burning stages, low- and intermediate-mass stars ($1 \lesssim M \lesssim 8 M_\odot$) enter the AGB phase, characterized by red colors and high luminosities. Most AGB stars are observed to have their surfaces contaminated with ashes of H- and He-burning, including s-process products. Theory relates these observations to the prediction that the structure of these stars is characterized by thin H- and He-burning shells, by the recurrent occurrence of convectively unstable so-called ‘thermal pulses’ in the He shell, and by the possibility of transport of part of the nuclearly processed material to the surface (‘third dredge-up’) and into the ISM (by strong winds).

Along these lines, it has been suggested by Cameron (e.g. Cameron 1985), and further studied by Jerry and some collaborators (Wasserburg et al. 1994) that AGB stars might have contributed appreciably to some short-lived isotopes in the ISM and

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4 Three nucleosynthetic processes are called for in order to explain the production of the stable nuclides heavier than iron. Two of them rely on neutron captures. In the so-called s-(slow-)process, a $\beta$-unstable nucleus, if produced, has in general time to decay before capturing a neutron. In such conditions, the corresponding nuclear flow is confined to the close vicinity of the line of nuclear stability, and the s-process thus produces the nuclei lying on this line. The reverse situation is encountered in the r-(rapid)process, where the neutron fluence is so high that the material is pushed deep inside the region of very neutron-rich $\beta$-unstable nuclei. If the neutron concentration decreases or even goes to zero, these nuclei cascade down to the valley of stability until a stable nucleus is reached. So, the r-process accounts for the neutron-rich stable heavy nuclei, and also complements the s-process contribution to the nuclei at the bottom of the valley of nuclear stability which are not bypassed from the r-process flow by a neutron-rich stable isobar. The third process, referred to as the p-process, accounts for the stable heavy neutron deficient nuclides. It is made of the destruction of pre-existing s- or r-nuclides by a variety of nuclear reactions involving the emission of a nucleon or of an $\alpha$-particle. While the s-process develops during non-explosive stages of the evolution of a large variety of stars, the r-process is likely associated with violent stellar phenomena, like supernovae. However, the precise site for this mechanism has not been identified yet. The p-process probably develops during SNII, and possibly also during the stages just preceding these explosions (see e.g. Arnould & Takahashi 1999 for more details).
in the early solar system. As Jerry is well known to be largely open to scientific debates about unsettled issues, he is most likely ready to acknowledge that the astrophysical plausibility of his contamination scenario and its true efficiency remain to be demonstrated.

Apart from the difficult problem of evaluating in astrophysical terms the probability for an AGB star to have been able to contaminate the forming solar system with short-lived radionuclides at the level required by laboratory data, many uncertainties remain in the precise evaluation of the radionuclide yields in terms of stellar mass and metallicity. One such major uncertainty concerns the efficiency of the source of neutrons leading to the development of the s-process in AGB stars. It is generally agreed today that $^{13}\text{C} (\alpha, n) ^{16}\text{O}$ is the relevant neutron producing reaction. The crux of the problem lies elsewhere, and more specifically in the prediction from ‘first principles’ of the available amount of $^{13}\text{C}$, which has to exceed largely the one emerging from the CNO burning of hydrogen in order to allow a fully developed s-process to operate (this extra $^{13}\text{C}$ is referred to as ‘primary’). In these matters, the theoretical challenge lies in the proper description of the mixing of matter across a H-He abundance discontinuity that develops in model stars. Such a mixing at the right level and with the correct depth distribution is indeed agreed to be a necessary condition to get the proper s-process. Recent works on that subject consider the effect of rotation (Langer et al. 1999) or of diffusive penetration of matter from the convective envelope into the underlying radiative layers (e.g. Herwig et al. 1997). These calculations provide a new basis for the study of the production of the primary $^{13}\text{C}$. Still, most predictions, and in particular those of Wasserburg et al. (1994), view the amount of that $^{13}\text{C}$ and its variation with position in the star as free parameters. Related uncertainties could of course be reduced on a case by case basis by trying to reproduce at best the s-process abundances observed at the surface of a given star (e.g. Gallino et al. 1998). This procedure would clearly be of the greatest value for better understanding the $^{13}\text{C}$ production mechanism if quantities like the stellar masses and metallicities of the considered stars were known, which is often not the case.

Another serious uncertainty relates to the quantity of C- and s-process-enriched matter dredged-up to the surface after each thermal pulse. In this field, too, significant progress has been made recently (e.g. Mowlavi 1999). The proper modeling of the dredge-up process and the reliable evaluation of the production of primary $^{13}\text{C}$ may actually be closely linked to each other. They would open the door to a more consistent study of the yields of short-lived isotopes from AGB stars.

Among those radionuclides, $^{26}\text{Al}$ holds a special position. It is demonstrated by now that $^{26}\text{Al}$ has been live in the early solar system (Sect. 3.1), and has also entered it in extinct form, carried by a variety of pre-solar grains (Sect. 3.7). As if this were not enough, $^{26}\text{Al}$ also exists in live form in the present ISM (Sect. 5.1).

On the theoretical side, $^{26}\text{Al}$ is essentially a product of the MgAl chain of hydrogen burning. This burning can occur in the H-rich shell of AGB stars. It could also develop in some $^{12}\text{C}$-rich layers below the H-He composition discontinuity which might engulf
enough protons for the Mg-Al chain to operate efficiently enough in order to dominate the $^{26}\text{Al}(n,p)^{26}\text{Mg}$ destruction due to the neutrons liberated by the radiative burning of the $^{13}\text{C}$ also produced in these layers. Hot enough pulses for neutrons to be liberated by $^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}$ could destroy part at least of the pre-pulse $^{26}\text{Al}$. A recent detailed discussion of the net $^{26}\text{Al}$ production by pulsing AGB stars can be found in Goriely (1999). These conclusions still need to be confirmed by AGB models producing consistently some primary $^{13}\text{C}$. Reliable yields from AGB stars are thus still awaiting improved stellar models, even for the ‘simple’ case of $^{26}\text{Al}$. 

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

Wolf-Rayet (WR) stars are generally considered to be the normal evolutionary phase of very massive stars ($M \gtrsim 20$ to $80 \, M_\odot$, depending upon their initial composition). Their structure, evolution and surface compositions are governed by huge non-explosive mass losses which can amount to as much as $10^{-4} \, M_\odot$/y. As a result of these spectacular winds, products of central hydrogen and even of central He burning can appear at the stellar surface, and be ejected into the interstellar medium. Apart from their role of strong interstellar medium chemical contamination, these winds have also a substantial dynamical effect of the WR surroundings. These stars are predicted to explode as SNIb/c (see above). The reader is referred to e.g. Arnould et al. (1997a) for a more detailed review of the observed properties of WR stars, as well as of some theoretical considerations.

Much progress has been made recently in the modeling of these stars. Many important observed features, like their luminosities, surface chemical compositions, or statistics in regions of constant star formation rate, as well as in starburst locations, can now be nicely accounted for by single non-rotating model stars (e.g. Maeder 1991,
Maeder & Meynet 1994). In spite of this success, uncertainties of course remain in the models. However, it has to be stressed also that the impact on the predictions of these uncertainties is largely reduced under the constraint that the largest possible body of observed intrinsic WR properties have to be reproduced at best. This favorable situation, combined with the fact that the modeling of single non-rotating WR stars is immensely simpler than the one of all the other short-lived radionuclide producers proposed up to now (and in particular of the AGB stars; see Sect. 3.3), forces to conclude that the predicted WR yields are likely to reach a level of reliability that cannot be obtained in the other cases. Of course, one has to remain alert to the fact that the WR structure and nucleosynthetic yield predictions might be affected by rotation, as well as by the binary nature of a non-negligible fraction of the WR stars. These effects are briefly discussed below.

The production of short-lived radionuclides of cosmochemical interest has been calculated in the framework of detailed evolution models for a large variety of non-rotating WR stars with different initial masses and compositions, and with the use of extended nuclear reaction networks. We first briefly review the special case of $^{26}$Al before considering the yields of other radionuclides of relevance.

The $^{26}$Al production by non-rotating WR stars A detailed discussion of the production of $^{26}$Al by the MgAl chain of hydrogen burning developing in WR stars has been conducted recently by Arnould et al. (1997b) and Meynet et al. (1997). Figure 3 displays some of their results in the form of the total mass $M_{26}(M_i, Z)$ of $^{26}$Al ejected by WR stars with various initial masses $M_i$ and metallicities $Z$. It shows that the $^{26}$Al yields increase with initial mass and $Z$, the $Z$ dependence being approximated by $M_{26}(M_i, Z) = (Z/Z_\odot)^2 M_{26}(M_i, Z_\odot)$, where $Z_\odot = 0.02$ is the solar metallicity. It is worth noticing that the $^{26}$Al yields of Meynet et al. (1997) are in qualitative agreement with those of Langer et al. (1995), even if these two sets of models greatly differ in their physical ingredients. This illustrates the statement made above concerning the reduced impact of remaining uncertainties in the models once they are constrained by observation.

An anonymous referee correctly argues that due account of observational constraints helps reducing uncertainties for all types of models, and not only in the WR case. However, it has to be emphasized that the difference between the number of theoretical ‘degrees of freedom’ and the observational constraints is much smaller in the WR case than in all the other possible radionuclide producers (like AGB stars, novae or supernovae of various types).
Effect of rotation on the WR production of $^{26}$Al  Rotation induces numerous dynamical instabilities in stellar interiors, and in particular meridional circulation and shear turbulence (e.g. Zahn 1992). The related mixing of the chemical species can deeply modify the chemical structure of a star and its evolution, and may in particular have important consequences on the $^{26}$Al production by WR stars. At present, very few rotating WR models address this question in detail (see Langer et al. 1995 for some preliminary results), so that it is certainly premature to quantitatively assess the possible role rotation plays in that respect. However, it seems safe to say that rotation increases the quantity of $^{26}$Al ejected by WR stellar winds. This claim is made plausible by Fig. 4, which shows the structural evolution during their H- and He-burning phases of two 60 M$_\odot$ stars that just differ by their rotational velocities. It appears that
1) The size of the convective core is enhanced by rotation;
2) Rapidly rotating stars may enter the WR phase while still on the Main Sequence. Moreover the surface abundances characteristic of their WNL and WC phases are not due to the mass loss which uncovers core layers, but result from diffusive mixing in the radiative zones. As a consequence, the evolution of the surface abundances are much smoother in rotating models;
3) The WR lifetime increases with $\Omega/\Omega_c$. In particular the WN stage during which $^{26}$Al is ejected, as well as the WN/WC transition phase, become much longer, so that much more mass is ejected during these phases. As a numerical example, the non-rotating model sketched in Fig. 4 ejects about 5 M$_\odot$ during the WN phase, while about 50 M$_\odot$ is ejected by the rotating model during the same phase.

The inference that rotation can enhance the $^{26}$Al yields of WR stars is confirmed by the numerical simulations of Langer et al. (1995) (see also the presupernovae evolution models for rotating massive stars computed by Heger 1998). Rotation also lowers the minimum initial mass of single stars which can go through a WR stage with a concomitant ejection of $^{26}$Al. It is thus likely to increase the net amount of $^{26}$Al ejected by WR stars in the ISM. This may be of relevance both to cosmochemistry and to $\gamma$-ray line astrophysics (Sect. 5) as well.

Effect of binarity on the WR production of $^{26}$Al  Tidal interactions in close binary systems may considerably modify the evolution of the two stellar components with respect to the one they would experience as isolated stars. Mass transfer by Roche Lobe Overflow can act as a strong stellar wind, and thus reduce the critical initial mass for producing single WR stars. Before any mass transfer, tidal effects are also expected to deform the star and therefore induce instabilities reminiscent of those induced by rotation. To our knowledge, the latter effect has never been studied in any detail,
even if it might have important consequences, like the homogenization of the stars, and the related inhibition of mass transfer. Other effects remain to be explored, like the impact of colliding winds on the mass transfer process, or even the very nature of the grains which can condense in colliding winds (see Sect. 3.7). Thus the effect of binarity on the WR star formation and evolution, and on the corresponding $^{26}$Al production cannot be evaluated with confidence at this time. Some preliminary estimates (Braun & Langer 1995) lead to the conclusion that ‘only for stars with masses $\leq 40 \, M_\odot$, binarity has the potential to increase the $^{26}$Al yield compared to the single star case’ (see also Langer et al. 1998). The fact that the situation may be quite different in more massive stars can be interpreted in the following way: after their Main Sequence, single high mass stars go through a LBV phase characterized by especially high stellar winds (see Fig. 4). Additional mass losses triggered by binarity would thus not induce more than a perturbation in the evolution of these stars. In contrast, lower initial mass stars not suffering the LBV winds would be drastically affected by Roche Lobe Overflow mass transfer, which acts as a strong wind not operating if the corresponding stars were isolated.

The extent in the reduction of the $^{26}$Al that can be ejected in the ISM by $M > 40 \, M_\odot$ WR members of binary systems cannot be ascertained at this point. It has clearly to depend on the fraction of the mass lost by the WR star which is accreted by its companion, and thus withdrawn from the ISM. In this scenario, however, one may wonder about the fate of the accreting companion, and about its net production or destruction of $^{26}$Al resulting from its evolution. Clearly, the effect of binarity on the net $^{26}$Al outcome by WR stars largely remains to be studied.

The WR production of other short-lived radionuclides A complementary detailed study of the production by non-rotating WR stars of other short-lived radionuclides of astrophysical and cosmochemical interest has been conducted by Arnould et al. (1997b). In short, their main results may be summarized as follows:

1. The neutrons released by $^{22}$Ne($\alpha$, 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 (see Fig. 4) 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. 5 shows that this agreement can be obtained for a time $\Delta^* \approx 2 \times 10^5$ y, where $\Delta^*$ designates the time elapsed between the last astrophysical event(s) able to affect the composition of the solar nebula and the

EDITOR: FIGURE 5 HERE
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 of course has to add $^{26}$Al (see above). 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. 5, 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. 5. 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) 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. 5, but also for the other cases considered by Arnould et al. (1997b). The interesting case of $^{205}$Pb is discussed further in Sect. 3.5;

(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 SNIIb/c explosion of the considered WR stars. This SN might add its share of radionuclides that are not produced abundantly enough prior to the explosion. This concerns in particular $^{53}$Mn, $^{60}$Fe or $^{146}$Sm, the latter case being discussed further in Sect. 3.6. One has also to acknowledge that the above conclusions sweep completely under the rug the possible role of rotation and binarity in the WR yields.

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. 5, 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.
3.5. $^{205}$Pb: a short-lived s-process chronometer?

Among the short-lived radionuclides of potential cosmochemical and astrophysical interest, $^{205}$Pb ($t_{1/2} = 1.5 \times 10^7$ y) has the distinctive property of being of pure s-process nature, at least if the $^{204}$Tl $\beta$-decay competes successfully with its neutron capture in stellar interiors. This remarkable feature has motivated 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 $9 \times 10^{-5}$ 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 $\beta$-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 by Jerry and one of his co-workers (Chen & Wasserburg 1987), leading to a value of about $3 \times 10^{-4}$. 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 $\beta$-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 Sect. 3.4). In view of the rather high predicted $^{205}$Pb WR yields (Fig. 5), one might wonder if the availability of reliable laboratory data for ($^{205}$Pb/$^{204}$Pb)$_0$ could not help discriminating a WR origin from other potential $^{205}$Pb sources, such as AGB stars (see Sect. 3.3). Of course, this question would be most profitably addressed if the $^{205}$Pb AGB yield predictions could be put 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.
3.6. $^{146}$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 $^{92}$Nb ($t_{1/2} = 3.6 \times 10^7$ y) and $^{146}$Sm ($t_{1/2} = 1.03 \times 10^8$ y) (Harper 1996, and references therein). The case of $^{92}$Nb 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 Audouze & Schramm (1972). This work has triggered a series of meteoritic, nuclear physics and astrophysics investigations, which have helped clarify many aspects of the question. In particular, Jerry and his collaborators (Prinzhofer et al. 1989) have contributed in an essential way to the reduction of the early uncertainties on the amount of $^{146}$Sm that has been injected live into the solar system through high quality measurements 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 to-day that $(^{146}{\text{Sm}}/^{144}{\text{Sm}})_0 = 0.008 \pm 0.001$, $^{144}$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 modeling of the p-process in massive stars, and especially in SNII (e.g. Arnould et al. 1998). In spite of this, the production ratio $P \equiv ^{146}{\text{Sm}}/^{144}{\text{Sm}}$ remains quite uncertain, being estimated by Somorjai et al. (1998) to lie in the $0.7 < P < 2$ range in (spherically symmetric) SNII models. This unfortunate situation relates in part to astrophysical problems, and in part to nuclear physics uncertainties, especially in the $^{148}$Gd ($\gamma, \alpha$)$^{144}$Sm to $^{148}$Gd ($\gamma, n$)$^{147}$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 $^{144}$Sm ($\alpha, \gamma$)$^{148}$Gd cross section down to energies very close to those of direct astrophysical interest, complemented with a better nuclear reaction model concerning in particular the appropriate low-energy α-particle nucleus optical potential (Somorjai et al. 1998).

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 $^{148}$Gd ($\gamma, \alpha$)$^{144}$Sm of direct astrophysical interest is reduced accordingly. This implies a lowering of the $^{144}$Sm production, and favors concomitantly the $^{146}$Sm synthesis through the main production channel $^{148}$Gd($\gamma,n$)$^{147}$Gd($\gamma,n$)$^{146}$Gd($\beta^+$)$^{146}$Sm. The net effect of the revised $^{148}$Gd ($\gamma, \alpha$)$^{144}$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 $^{148}$Gd ($\gamma, n$)$^{147}$Gd reaction, for which no experimental information can be foreseen in a very near future in view of the unstable
nature of \(^{147}\text{Gd}\) \((t_{1/2} \approx 38 \text{ h})\). 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 in SNII, one has to conclude that \(^{146}\text{Sm}\) cannot be viewed at this point as a reliable \(p\)-process chronometer. Further uncertainties arise, relating in particular to the possibility of additional, and still poorly studied, \(^{146}\text{Sm}\) production by SNIa, as well as by exploding SN Ib/Ic WR stars, which could in fact release the same suite of radionuclides as SNII.

3.7. Extinct short-lived radionuclides in the solar system

The year 1987 has marked the start of the discovery and isolation of meteoritic grains that are interpreted as specks of stardust having survived the formation of the solar system. Since that time, a remarkable series of dedicated laboratory work has been conducted, and has led by now to the identification and analysis of a long suite of such presolar grains. They are made of refractory materials of various types (diamond, SiC, graphite, corundum, silicon nitride). Tiny subgrains, in particular Ti-, Zr- and Mo-carbide or TiC subgrains, have even been found 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 \(^{26}\text{Mg}\) excesses attributed to the in situ decay of \(^{26}\text{Al}\) 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 \(^{26}\text{Al}/^{27}\text{Al}\) 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 \((^{26}\text{Al}/^{27}\text{Al})_0 \approx 5 \times 10^{-5}\) (Sect. 3.1). The highest reported ratios obviously put particularly drastic constraints on the \(^{26}\text{Al}\) 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 \(^{26}\text{Al}/^{27}\text{Al}\) 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 yet that the types of grains loaded with large \(^{26}\text{Al}\) amounts can indeed condense from the WR wind.\(^6\)

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 \(^{22}\text{Ne}\) (e.g. Amari et al. 1995). This remarkable feature is generally interpreted in terms

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\(^6\)As emphasized in several places (Arnould et al. 1997a, 1997b), binarity might affect the chemistry and nature of the grains known to form around WR stars. In fact, it has been speculated that a recently discovered singular presolar SiC grain might find its origin in a WR-O binary system (Amari et al. 1999)
of the in situ decay of the ultra-short radionuclide $^{22}\text{Na}$ ($t_{1/2} \approx 2.6$ y). In view of its short lifetime, the production of $^{22}\text{Na}$ 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. Over the years, many calculations have been carried out along these lines (e.g. José et al. 1998 for a recent study). Supernovae could also be $^{22}\text{Na}$ 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 also carry $^{41}\text{K}$ excesses of up to two times solar that are attributed to the in situ decay of $^{41}\text{Ca}$ ($t_{1/2} = 10^5$ y). From these observations, the initial $^{41}\text{Ca}$ abundances are inferred to lie in the $10^{-3} \lesssim ^{41}\text{Ca}/^{40}\text{Ca} \lesssim 10^{-2}$ range (Amari & Zinner 1997). The $^{41}\text{Ca}$ 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) $^{41}\text{Ca}$ 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 $^{41}\text{Ca}$ whose abundance relative to $^{40}\text{Ca}$ 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 accompany the $^{41}\text{K}$ excess, and in particular an inferred $^{26}\text{Al}/^{27}\text{Al}$ ratio ranging typically between 0.01 and 0.1.

In order to account for these correlated anomalies, large scale mixing of ad hoc amounts of SNII layers with different compositions has been proposed (Travaglio et al. 1998). If the very existence of such a mixing is supported by observation (e.g. Nagataki 1999 for references), it remains to model it and the associated composition pattern in a reliable way, which is far from being the case at present (e.g. Nagataki 1999 for comments and references). Even the presupernova composition may be less well predictable than generally imagined (e.g. Bazan & Arnett 1998). In view of these many difficult pending problems, it is quite risky to try evaluating the plausibility of the blends of supernova layers that are called for in order to fit the observed anomalies.

Finally, evidence for the presence of $^{44}\text{Ti}$ ($t_{1/2} \approx 60$ y) in some graphite and SiC-X grains is provided by $^{44}\text{Ca}$ excesses that translate into $^{44}\text{Ca}/^{40}\text{Ca}$ 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 SNII 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. The isotopic anomalies that correlate

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7 The two forms of Ne-E identified today, Ne-E(L) and Ne-E(H), were not known at that time. It is generally considered by now that the less extreme $^{22}\text{Ne}$ enrichments exhibited by Ne-E(H) do not require a $^{22}\text{Na}$-decay origin. In fact, the ejecta of AGB and WR stars are enriched in $^{22}\text{Ne}$. It may also be of interest to note that WR stars have been considered as responsible for a $^{22}\text{Ne}$ excess observed in the Galactic Cosmic Rays (Arnould 1984).
with the $^{44}$Ca excess are often considered to demonstrate a SNII origin of the carrier grains (Nittler et al. 1996). Again, a large mixing of ad hoc amounts of different SN layers has to be postulated, and the possibility of getting just the right mixing of course remains to be demonstrated.

It has also been proposed (Clayton et al. 1997) that the correlated anomalies carried by the SiC - X grains, including the $^{44}$Ti-related anomaly, present evidence for a SNIa origin. Clearly, this model alleviates the mixing problem just mentioned, but raises other highly complex questions. In particular, and as acknowledged by Clayton et al. (1997), the progenitors and the evolution to explosion of SNIa are far less well understood than in the SNII case. In such conditions, it is not known at this time if nature can really provide the conditions that would be required for producing SiC-X grains with the right load of isotopic anomalies.

4. Spallative production of short-lived radionuclides

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 plausibility of such an enhancement is supported by a variety of observations of ‘Young Stellar Objects (YSOs)’.

Jerry and one of the authors (M.A.) have revisited this question more than a decade ago (Wasserburg & Arnould 1987) in an attempt to identify a possible relationship between the early solar activity and the extinct $^{26}$Al and $^{53}$Mn in meteorites. This is just one in a series of investigations dealing with the spallation scenario, which has been the subject of a recent and renewed interest. One has to acknowledge that, in spite of some success, the various studies conducted along these lines reach the conclusion that it appears difficult to account for the production of all the relevant short-lived radionuclides in proportions compatible with the observations, at least without invoking a prohibitive number of ‘tooth fairies’ (e.g. Podosek & Nichols 1997 for references; also Lee et al. 1998 and Sahijpal et al. 1998).

It may be worth noting that Wasserburg & Arnould (1987) stress the possible interest, and identify some consequences, of envisioning spallation scenarios in which the ratio of $\alpha$-particle to proton fluences would be higher than in the solar nebula. Such a situation might be prevailing around H-depleted WR stars. In this scenario, spallation
and thermonuclear production of short-lived radionuclides might just be indissolubly complementary. It is our opinion that these speculations deserve further scrutiny.

5. Gamma-ray line astrophysics

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 ISM 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 $\gamma$-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 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. This complementarity has not escaped Jerry’s curiosity (Qian et al. 1998).

On the observational side, $\gamma$-ray line astronomy has received considerable momentum in the 80s with the detection of $^{26}$Al in the Milky Way. It has now been promoted to a mature astrophysical discipline following the discovery of additional lines from the $^{56}$Ni $\rightarrow$ $^{56}$Co $\rightarrow$ $^{56}$Fe disintegration chain in the supernovae SN1987A and SN1991T, from the $^{57}$Co $\rightarrow$ $^{57}$Fe in SN1987A, and from $^{44}$Ti $\rightarrow$ $^{44}$Sc $\rightarrow$ $^{44}$Ca in the CasA and J052-4642 (Iyudin et al. 1998) supernova remnants.

These observations have been complemented with a substantial amount of theoretical effort in order not only to interpret the available data, but also to predict other potential $\gamma$-ray line candidates. Among them, $^{22}$Na and $^{60}$Fe are of special interest (see Arnould & Prantzos 1999 or Diehl & Timmes 1998 for recent reviews).

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 for it to be an interesting candidate for $\gamma$-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 $\gamma$-rays; these photons are thus degraded in energy as they interact with the surrounding material. The $\gamma$-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 $\gamma$-ray line candidates (see Sect. 5.1 for a brief account of the $^{26}$Al production in relation with $\gamma$-ray line observations). 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 $\gamma$-ray line observability. The situation is, in fact, quite different when dealing with SNIa explosions of low-mass stars, or with SNII explosions of massive stars. The SNIa ejecta reach low opacities much more quickly than the SNII ones in view of their lower masses (about $1\, M_\odot$) and larger ejection velocities (in excess of $1.5 \times 10^4\, \text{km/s}$). More specifically, the ejecta become transparent to $\gamma$-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 $\gamma$-ray line associated with the decay of the important nuclide $^{56}\text{Ni}$, whose half-life is only 6 days.

5.1. The case of $^{26}\text{Al}$

Not content with playing a very special role in cosmochemistry, $^{26}\text{Al}$ has also been responsible for the birth of $\gamma$-ray line astrophysics with the observation in the present ISM of the 1.8 MeV $\gamma$-ray line emitted following the de-excitation of the $^{26}\text{Mg}$ produced by the $^{26}\text{Al}$ $\beta$-decay.

The data available to-date indicate that the present ISM contains about $2\, M_\odot$ of $^{26}\text{Al}$, the distribution of which excludes (i) a unique point source in the galactic center, (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, like novae or low-mass AGB stars. In contrast, they favor massive stars (WR stars and/or SNIIb/Ic and SNII) as the $^{26}\text{Al}$ production sites (e.g. Knödlseder et al. 1999). They suggest in fact that most of the $^{26}\text{Al}$ is made by high metallicity WR stars in the inner Galaxy.

The $^{26}\text{Al}$ yields from non-rotating WR stars predicted as reviewed in Sect. 3.4 have been used to evaluate quantitatively the virtues of these stars as sources of the 1.8 MeV line in the present ISM. Figure 6 shows the mass of live $^{26}\text{Al}$ deposited by the winds of WR stars in rings of increasing galactocentric radius. This estimate is based on the metallicity dependent yields computed by Meynet et al. (1997), and on their assumptions concerning in particular the Initial Mass Function, and the galactocentric radius dependence of the star formation rate and of the metallicity (for details, see their Sect. 4.1). The signature of the $\sim 5\, \text{kpc}$ ring of molecular clouds located at the galactocentric radius of about 5 kpc is clearly seen. It is also predicted that more than half of the total $^{26}\text{Al}$ mass is contained within this ring.

The integration of the histogram of Fig. 6 over the galactic radius leads to a total galactic mass of $1.15\, M_\odot$ produced solely by non rotating non-exploding WR stars. Due consideration of various uncertainties leads to masses in the probable 0.4-1.3 $M_\odot$ range (Meynet et al. 1997), so that the considered stars might account for 20 to 70% of the present galactic $^{26}\text{Al}$.

EDITOR: FIGURE 6 HERE

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As already stressed in Sect. 3.4, these results may have to be changed when rotation
and/or binarity are taken into account. In fact, rotation increases the total contribution
of WR stars to the galactic $^{26}\text{Al}$ by lowering the minimum initial mass star of single
stars which can go through a WR phase. It is not possible to be more quantitative
on this point at present. A detailed evaluation of the global $^{26}\text{Al}$ galactic input by
rotating WR stars indeed requires the computation of a grid of models with different
initial masses, metallicities and rotation rates, as well as the convolution of yields from
individual stars with an observed distribution of rotational velocities. As far as binarity
is concerned, preliminary computations suggest that it might increase the $^{26}\text{Al}$ yields
computed for single stars for WR initial masses lower than about 40 $M_{\odot}$, the reverse
effect being obtained for more massive stars. Clearly, this important question deserves
further studies. This is even more the case following recent observations of the $\gamma^2$ Vel
binary system.

The $\gamma^2$ Vel system  The presently available observations cannot help disentangling the
relative contributions of non-exploding WR stars, exploding ones (SNIIb/Ic) and SNII
to the present $^{26}\text{Al}$ galactic content. In this respect, a recent observation of high value
provides an upper limit of about $10^{-5}\text{ ph cm}^{-2}\text{s}^{-1}$ for the 1.8 MeV luminosity of the
$\gamma^2$ Vel binary system containing an O-type and a WR star (of WC8 subtype, Diehl et
al. 1999). In order to evaluate the compatibility of this observation with predictions,

at least the initial mass and metallicity of the WR progenitor, as well as the age of
$\gamma^2$ Vel have to be known. The proximity of $\gamma^2$ Vel justifies the use of solar metallicity
stellar models. Non-rotating single star models (Meynet et al. 1994), combined with
the position of the O-star component in the HR diagram, lead to an age between 3.5
and 4.5 My, and an initial WR mass between 40 and 60 $M_{\odot}$ (Schaerer et al. 1997). A 60
$M_{\odot}$ WR progenitor is predicted to have a 1.8 MeV luminosity exceeding the observed
upper limit by a factor of about 2, while the calculated luminosity lies below this limit
in the case of a 40 $M_{\odot}$ model star. From these considerations alone, one can conclude
that the observed upper limit is compatible with the predictions for $M < 40 M_{\odot}$ single,
non-rotating and non-exploding WR stars. Of course, $\gamma^2$ Vel is a binary system. As
discussed above, a $M \gtrsim 40 M_{\odot}$ WR component cannot be excluded by the observation
of Diehl et al. (1999) if indeed a large enough fraction of its $^{26}\text{Al}$-loaded ejecta is accreted
by its O-star companion.

6. Summary and perspectives

The decay of a variety of nuclides with half-lives ranging from some years to billions
of years probably originating from outside the solar system are now recorded in live or
fossil form in the solar system. These findings bring a rich variety of information about
a vast diversity of highly interesting astrophysical questions, some of which are briefly
reviewed here with special emphasis on the contribution of Jerry Wasserburg to this
broadly interdisciplinary field of research.
First, the virtues of the long-lived (half-lives \( t_{1/2} \) close to, or in excess of \( 10^9 \) y) radionuclides as galactic chronometers are discussed in the light of recent observational and theoretical works. It is concluded that the trans-actinide clocks based on the solar system abundances of \(^{232}\text{Th}, ^{235}\text{U}\) and \(^{238}\text{U}\) or on the \(^{232}\text{Th}\) surface content of some old stars are still unable to meaningfully complement galactic age estimates derived from other independent astrophysical methods. In this respect, there is reasonable hope that the \(^{187}\text{Re}-^{187}\text{Os}\) chronometric pair could offer better prospects. The special case of \(^{176}\text{Lu}\), which is a pure s-process product, is also reviewed. It is generally considered today that this radionuclide cannot be viewed as a reliable s-process chronometer.

Second, we comment on the astrophysical messages that could be brought by short-lived radionuclides (\( 10^5 \lesssim t_{1/2} \lesssim 10^8 \) y) that have been present in live or in fossil form in the early solar system. From an astrophysical point of view, the demonstrated early existence of live short-lived radionuclides is generally considered to provide the most sensitive radiometric probe concerning discrete nucleosynthetic events that presumably contaminated the solar system at times between about \( 10^5 \) and \( 10^8 \) y prior to the isolation of the solar material from the general galactic material. Of course, this assumes implicitly that the radionuclides of interest have not been synthesized in the solar system itself. This is still a matter of debate, as we briefly stress. If indeed the short-lived radionuclides that have been present live in the early solar system are not of local origin, the external contaminating agents that have been envisioned are supernovae, evolved stars of the Asymptotic Giant Branch (AGB) type, or massive mass-losing stars of the Wolf-Rayet (WR) type. We comment especially on some aspects of the AGB or WR contamination. In the latter case, we discuss more specifically the role of rotation and of binarity on the predicted yields of \(^{26}\text{Al}\), a radionuclide of special cosmochemistry and astrophysics interest. Some comments are also devoted to \(^{146}\text{Sm}\) and \(^{205}\text{Pb}\). The former one is a short-lived p-process radionuclide that has most probably been in live form in the solar system, while the latter one is of s-process origin. It is shown to raise interesting nuclear physics and astrophysics questions, and to deserve further cosmochemical studies in order to evaluate its probability of existence in live form in the early solar system.

Third, the case of extinct short-lived radioactivities carried by pre-solar grains is shortly mentioned, and some comments are made about the possible origin of these grains.

Finally, a brief mention is made to \( \gamma \)-ray line astrophysics, which provides interesting information on live short-lived radionuclides in the present interstellar medium, and thus complements in a very important way the study of extinct radionuclides in meteorites. This is illustrated with the case of \(^{26}\text{Al}\).

Jerry Wasserburg has written important pages of many chapters of this ‘astrophysics of cosmic radioactivities’ with his incomparable dynamism and competence. He has without doubt triggered much work in the field and shown many new ways. For sure,
it must be most gratifying for him to know that so much remains to be done and said, and that each day brings its share of renewed excitement and laboratory discoveries.

Acknowledgments The authors are grateful to Larry Nittler and to an anonymous referee for their very careful reading of the manuscript, and for their many comments.
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FIGURE CAPTIONS

**Figure 1** Ages of the Universe ($T_U$), of galactic globular clusters ($T_{GC}$) and of the galactic disc ($T_{disc}$). Estimates from cosmological models are specified for the standard hot Big Bang model by values of $\Omega_0$, the ratio of the present density of the Universe to the critical density that would make it ‘flat’ (zero space curvature). Predictions are also displayed for a non-standard flat model with a non-zero cosmological constant in terms of the so-called deceleration parameter $q_0$, which equals $3\Omega_0/2 - 1$ in the considered model (e.g. Tayler 1986 for more details). In both cases, the displayed ranges correspond to values $100 \geq H_0 (\text{km/s/Mpc}) \geq 50$ of the Hubble constant $H_0$ at the present time. Adopted values of the redshift $z$ due to the Hubble expansion are also given; these values are in no way meant to be precise. The label SNIa defines the age limits derived from values of those cosmological model parameters that are determined with the use of SNIa as standardized candles. The ages derived from HRD analyses of globular clusters or open clusters are in the ranges labelled GC and OC, respectively. The predictions based on white dwarf luminosity functions are noted WD, while the nucleo-cosmochronological evaluations of the age $T_{\text{nuc}}$ of the nuclides in the solar system are marked with the label SS (from Arnould & Takahashi 1999, where more details and references can be found).

**Figure 2** Mass of $^{26}\text{Al}$, in solar units and as a function of time (i.e. of the thermal pulse number), predicted in the intershell layers of a $2.5 M_\odot$ solar metallicity AGB star. $^{26}\text{M}_\text{H}$ (filled circles) is the total $^{26}\text{Al}$ mass left over by the H-burning shell in those layers not engulfed by the next pulse convective tongue. That mass is directly brought to the surface during the dredge-up episodes. $^{26}\text{M}_\text{He}$ (open circles) is the total mass of $^{26}\text{Al}$ present in the C-rich layers left over by the pulse convective tongue. Part of this $^{26}\text{Al}$ (up to 40% according to recent calculations by Mowlavi 1999; see also Goriely 1999) is eventually mixed into the envelope during the dredge-up episode. The production of primary $^{13}\text{C}$, and the possible resulting destruction of a fraction of $^{26}\text{M}_\text{He}$, is not included in the calculations. Each symbol corresponds to a thermal pulse.

**Figure 3** Masses of $^{26}\text{Al}$ ejected by WR stars of different initial masses and metallicities $Z$ at the end of its WC-WO phase (from Meynet et al. 1997, referred to as ‘present work’). The predictions of $Z = 0.02$ WR models computed by Langer et al. (1995) are also displayed for comparison.

**Figure 4** Evolution of the total mass $M_{\text{TOT}}$ and of the mass of the convective core $M_{\text{CONV}}$ as a function of time for a non-rotating 60 $M_\odot$ model star ($\Omega = 0$), and for a star that just differs by its angular velocity $\Omega = 0.6\Omega_c$, where $\Omega_c$ is the break-up angular velocity. The ordinate displays the mass $M$ at a given point inside the star normalized
to the mass of the Sun. In this scale $M = 0$ and $M = M_{\text{TOT}}$ correspond to the stellar center and surface, respectively. Various evolutionary stages are indicated on the right at the corresponding values of $M_{\text{TOT}}$

**Figure 5** Abundance ratios $(R/S)_0$ of various radionuclides $R$ relative to stable neighbors $S$ for a 60 $M_\odot$ model star with $Z = 0.02$ versus $\Delta^*$, interpreted as the period of free decay elapsed between the production of the radionuclides and their incorporation into forming solar system solids. All the displayed ratios are normalized to $(^{107}\text{Pd}/^{108}\text{Pd})_0 = 2 \times 10^{-5}$ (e.g. Wasserburg 1985) through the application of a common factor $d(\Delta^*)$, which may be seen as a ‘dilution’ factor measuring the fraction of the produced radionuclides that has been effectively able to contaminate the solar system. The values of this factor are indicated on the Pd horizontal line for 3 values of $\Delta^*$. 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 $(^{205}\text{Pb}/^{204}\text{Pb})_0 \approx 3 \times 10^{-4}$ (not shown)] (see Arnould et al. (1997b) for more details)

**Figure 6** Galactocentric radius dependence of the mass of $^{26}\text{Al}$ ejected by non-rotating non-exploding WR stars. The Galaxy is divided into 15 concentric rings with 1 kpc width. More computational details are provided in the main text (taken from Arnould et al. 1997)
Figure 1.
Figure 2.
Figure 3.
Figure 4.
Figure 5.
Figure 6.

Total Mass
from WR stars = 1.15 $M_\odot$