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Short-lived radionuclide production by non-exploding Wolf-Rayet stars

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Abstract. This paper presents an extension and update of previous calculations of the production by non-exploding Wolf-Rayet stars of radionuclides that could be responsible for certain isotopic anomalies discovered in meteoritic inclusions, or in meteoritic grains of probable circumstellar origin.

Quantitative predictions of the time dependence of the radionuclide composition of the wind of Wolf-Rayet stars with initial masses in the wide $25 \leq M_{\rm i} \leq 120\,{\rm M}_{\odot}$ range and for metallicities $0.001 \leq Z \leq 0.04$ are obtained from a set of revised stellar evolution models. Special emphasis is put on the radionuclides with half-lives between about 10^5 and 10^8 y that could be produced by neutron captures during central helium burning and ejected during the WC-WO evolutionary phases. We stress that the radionuclide yield predictions are much more secure for Wolf-Rayet stars than for any other potential source of these species that has been contemplated up to now. This relates directly to the simplicity of these stars compared to highly difficult to model objects like Asymptotic Giant Branch stars, novae or supernovae.

Our abundance predictions are confronted with existing observational data, or are hoped to help unravelling cases of potential interest for further laboratory quest when observations are lacking. The case of ^{26}Al, of special interest for γ-ray line astronomy as well as for cosmochemistry, is also briefly revisited. In contrast to the other considered radionuclides, ^{26}Al is produced during hydrogen burning, and is ejected at the WN evolutionary phase of the Wolf-Rayet stars. Our computed yields are also used as the basis for a qualitative discussion of the astrophysical plausibility of the contamination of the protosolar nebula with the radionuclides loading the Wolf-Rayet winds.

Our calculations indicate that ^{26}Al, ^{41}Ca and ^{107}Pd can be produced at a level compatible with the observations from a large variety of Wolf-Rayet stars with different masses and initial compositions. Wolf-Rayet stars could also account for the very uncertain limits set on $(^{36}{\rm Cl})_0$ and $(^{205}{\rm Pb})_0$. In addition, ^{93}Zr, ^{97}Tc, ^{99}Tc and ^{135}Cs are predicted to be produced in more or less large amounts, but the lack of secure experimental data prevents any meaningful confrontation with the observations. In contrast, the considered stars cannot explain the limits set recently on the amount $(^{60}{\rm Fe})_0$ of ^{60}Fe that was live at the start of the condensation sequence in the solar system. Other radionuclides of interest (^{53}Mn, ^{92}Nb, ^{129}I, ^{146}Sm, ^{182}Hf, ^{244}Pu) cannot be produced either during the non-explosive evolution of the Wolf-Rayet stars, but could be synthesized during their eventual supernova explosion.

Key words: nuclear reactions, nucleosynthesis – stars: abundances – stars: Wolf-Rayet – solar system: meteors, meteoroids – stars: formation

1. Introduction

There is now evidence, ranging from strong to marginal, for the signature of the in-situ decay of radionuclides with half-lives from about 10^5 to approximately 10^8 y in meteoritic material of solar-system origin. Such observations are generally interpreted in terms of the injection of these live radionuclides in the solar nebula, followed by their trapping into condensing solids. In such views, important information can be gained on some exciting astrophysical questions relating to the formation and early history of the solar system, and in particular on the time Δ^* elapsed between the last astrophysical event(s) able to affect the composition of the solar nebula and the solidification of some of its material. For a recent general review, the reader is referred to e.g. Swindle (1993) and references therein.

More recently, information gained from the study of solar-system solids has been complemented with the discovery that ^{26}Al was carried by silicon carbide, graphite and oxide grains of supposedly circumstellar origin (Anders and Zinner 1993, Ott 1993, Hoppe et al. 1994, Hutcheon et al. 1994, Nittler et al. 1994).

Several synopses of the possible astrophysical sources of the short-lived radionuclides have been prepared recently (e.g.

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Swindle 1993, where a list of relevant references is also provided). The proposed progenitors include non-stellar spallative sources, as well as stars of various types, like Asymptotic Giant Branch stars (see also Wasserburg et al. 1994), novae (see also Politano et al. 1995), supernovae (see also Cameron et al. 1995), and massive mass losing stars. Clearly, none of these models is able to account for the whole series of data gathered on the short-lived radionuclides present in the early solar system, and all of them face problems of their own.

This paper aims at revisiting the role possibly played in the radionuclide contamination of the forming solar system by Wolf-Rayet (WR) stars. For many reasons, these objects are appealing contributors to the isotopic anomalies in general, and to the radionuclides in particular. This is so especially because they are observed to lose mass at very large rates that can exceed $10^{-5}\,M_\odot\,y^{-1}$, the ejected mass being contaminated with the products of hydrogen and helium burnings. In addition, certain WR stars are known to make dust in their winds (e.g. Williams 1995, and references therein). Finally, the role of WR stars would be well in line with the "bing bang" model for the isotopic anomalies promoted by Reeves (1978).

Wolf-Rayet stars are also very attractive "technically". These stars are indeed expected to be in mechanically "stable" evolutionary stages. In fact, their observed spectroscopic subclasses correspond to central hydrogen or helium burning, the very brief subsequent non-explosive burning phases having essentially no detectable signature. The modelling of those objects is thus immensely easier and more reliable than the one of all the other possible anomaly progenitors. This is even more so as the impact of uncertainties remaining in e.g. the mass loss rates or the description of the convective cores is drastically reduced once the models are constrained to reproduce at best the many available observational data. In such conditions, we claim that the yield *predictions* are of higher quality in the WR case than for all the other potential stellar sources of isotopic anomalies[1].

We present here an extension and update of previous calculations (Arnould and Prantzos 1986, Arnould 1993, Meynet and Arnould 1993) of the WR yields of radionuclides that could load circumstellar WR grains, or contaminate the gas of the protosolar nebula.

The calculations are performed for WR model stars in a wide range of initial masses and compositions. The evolutionary and nucleosynthesis models are briefly described in Sect. 2. Some characteristics of the calculated WR structural evolution of relevance here are presented in Sect. 3, along with the wind content of radionuclides that are considered to be responsible for certain observed anomalies. These predictions are confronted with existing data (Sect. 4). Yields of radionuclides that could lead to anomalies which remain unobserved at present are also presented in order to help unravelling cases of potential interest for further laboratory quest. In the light of our predicted radionuclide content of the WR winds, Sect. 5 discusses in a qualitative way the astrophysical plausibility of the contamination of the protosolar nebula with the radionuclides loading the WR ejecta. Conclusions are drawn in Sect. 6. Non-radiogenic isotopic anomalies in the elements from carbon to lead that are predicted to be carried by the winds of WR stars will be discussed elsewhere.

[1] Specific problems may be raised by the binary nature of certain WR stars. They are neglected here.

2. The stellar and nucleosynthesis model

Evolutionary sequences are computed from the "Zero Age Main Sequence (ZAMS)" to the end of central carbon burning for stars with initial masses M_i = 25, 40, 60, 85 and 120 $M_\odot$, and metallicities (i. e. the total mass fraction of all the nuclides heavier than H and He) $Z = 0.001, 0.004, 0.008, 0.02$ (the solar metallicity, referred to in the following as $Z_\odot$). Models with Z = 0.04 are also constructed for $M_\mathrm{i} = 25, 60, 85$ and 120 $M_\odot$. Apart from the nuclear physics input, the computations are carried out as described by Meynet et al. (1994). In particular,

1. enhanced mass loss rates with respect to those adopted in previous calculations (Schaller et al. 1992) are used during the main sequence and WNL phases (see below). Such an enhancement seems to be required for reproducing the luminosities, surface abundances and populations of WR stars in starbursts and in zones of constant star formation rate (Maeder and Meynet 1994, Meynet 1995);
2. the models are computed with a moderate core overshooting characterized by $d/H_\mathrm{p} = 0.20$, where d is the overshooting distance, and H_p the pressure scale height at the boundary of the classical core;
3. the new OPAL radiative opacities (Rogers and Iglesias 1992) are used. At low temperatures, these data are complemented with the atomic and molecular opacities from Kurucz (1991).

As far as energy production and nucleosynthesis are concerned, the H-burning network used by Meynet et al. (1994) is substantially expanded by duly taking the NeNa and MgAl burning modes into account, and in particular all the channels leading to the production and destruction of ^{26}Al. The corresponding network and adopted reaction rates are described in Arnould and Mowlavi (1993). A noticeable exception concerns the $^{26}\mathrm{Al}(\mathrm{p},\gamma)^{27}\mathrm{Si}$ reaction rate, which is selected from Champagne et al. (1993).

A limited He-burning network is used in order to evaluate the nuclear energy production (Schaller et al. 1992). Use is still made of the $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ reaction rate recommended by Caughlan et al. (1985), which is about 2.5 times larger than the value adopted by Caughlan and Fowler (1988)[2].

The stellar models obtained as described above have been post-processed with a detailed network including all the neutron sources and neutron capturers between C and Bi in order to follow the s-process operating during He burning. It has to be

[2] Recent experimental data concerning the E1 contribution to the rate (Zhao et al. 1993; Azuma et al. 1994) complemented with theoretical evaluations of the E2 component based on a microscopic model (Descouvemont 1993) lead to a rate that is intermediate between the rates proposed by Caughlan et al. (1985) and Caughlan and Fowler (1988).

emphasized that the adopted decoupling between the calculated stellar structure and s-process nucleosynthesis, while saving a considerable amount of computer time, is fully justified during core He-burning in massive stars, as can be inferred from a discussion by Langer et al. (1989).

The s-process network, the details of which have already been presented by Prantzos et al. (1990), includes in particular the following radionuclides with half-lives between about 10^5 and 10^8 y that are of cosmochemical interest: ^{26}Al, ^{36}Cl, ^{41}Ca, ^{60}Fe, ^{81}Kr, ^{93}Zr, ^{97}Tc, ^{98}Tc, ^{99}Tc, ^{107}Pd, ^{129}I, ^{135}Cs, ^{146}Sm, ^{182}Hf and ^{205}Pb.

Some of the nuclear reaction rates involved in the s-process network have been updated. In particular, the rate of the ^{22}Ne-producing $^{18}\mathrm{O}(\alpha,\gamma)^{22}\mathrm{Ne}$ reaction is taken from Giesen et al. (1994). On the other hand, use is made of the rates of the $^{13}\mathrm{C}(\alpha,\mathrm{n})^{16}\mathrm{O}$ and $^{22}\mathrm{Ne}(\alpha,\mathrm{n})^{25}\mathrm{Mg}$ neutron producing channels that have been derived recently (Drotleff et al. 1993), the rate of the competing $^{22}\mathrm{Ne}(\alpha,\gamma)^{26}\mathrm{Mg}$ channel being adopted from Wolke et al. (1989) (see e.g. Meynet and Arnould 1993 for an illustration of the impact of the new rates of the neutron producing reactions on the s-process yields from central He burning in massive stars).

As far as the neutron captures are concerned, the (n,γ) rates are taken from the compilation by Beer et al. (1992), or from Hauser-Feshbach model calculations (Thielemann et al. 1986) for neutron captures by unstable nuclides. This same model is also used for predicting the rates of the (n,p) and (n,α) reactions included in the s-process network. An important exception to this concerns the (n,p) and (n,α) reaction rates on ^{40}K, which are adopted from Weigmann et al. (1981), and on ^{41}Ca, for which recent experimental data have been obtained by Wagemans et al. (1993).

3. Results

3.1. Internal WR structural evolution

Figure 1 displays the structural evolution of the $60\,\mathrm{M}_\odot$ model star with $Z = 0.02$, as well as the sequence of spectroscopic subclasses through which it is evolving. After the main sequence, a very brief Luminous Blue Variable (LBV) phase is experienced, during which about $5\,\mathrm{M}_\odot$ are lost in less than 10^4 y. It is followed by a WN phase that lasts for about 10^5 y, and then by a WC-WO stage. By the end of this phase, the star has lost about 90% of its original mass through its intense wind. In fact, this huge mass loss is responsible for the sequence of WR spectroscopic classes which actually characterize the composition of the stellar surface, and consequently of the wind.

The time changes of the WR surface composition can be inferred from Fig. 1. From the main sequence, the convective H-burning core recedes in mass with time, leaving in its wake a gradient of chemical composition. At time $t \approx 3.1\ 10^6$ y, the total mass of the star (reduced by stellar winds) is equal to the mass of the H-burning convective core at its maximum extent. From this stage onwards, and until the entrance into the WC phase, the surface abundances, and therefore the matter ejected by the stellar winds, bear the imprints of the CNO processed material (low C/N and O/N ratios as compared to cosmic abundances), and is also enriched with ^{26}Al synthesized in the H-burning convective core by the MgAl chain. This evolutionary phase comprises the LBL and WN classes, the latter one being defined to start when the surface mass fraction of hydrogen decreases below 0.4 (Schaller et al. 1992).

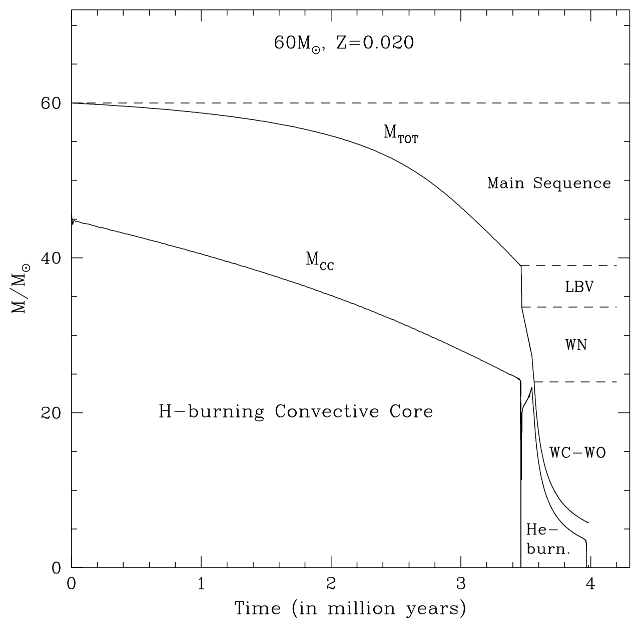

Fig. 1. Evolution of the total mass M_{TOT} and of the convective core mass M_{cc} as a function of time for a $60\,\mathrm{M}_\odot$ model with solar (Z = 0.02) metallicity (Meynet et al. 1994). The different stages through which the evolution proceeds are indicated on the right of the figure: LBV stands for Luminous Blue Variable, WN and WC-WO for the WR phases during which the surface is enriched in nitrogen (H-burning product) and in carbon-oxygen (He-burning products), respectively

When the He-burning products start appearing at its surface, the star becomes a WC star. This phase, which can turn into a WO stage (e. g. Smith and Maeder 1991, Kingsburgh et al. 1995), lasts until the star's eventual supernova explosion. In the following, no distinction will be made between the WC and WO subtypes. They will be referred generically to as the WC-WO phase. All along this WC-WO stage, the s-process nuclides synthesized during the core He-burning phase are ejected into the interstellar medium.

3.2. The wind composition

The computed stellar evolutionary sequences allow us to calculate in a self-consistent way the composition at each instant of the ejected wind, as well as the integrated mass $M_{\mathrm{R}}^{\mathrm{w}}(t_{\mathrm{b}}, t)$ of radionuclide R ejected by the wind of a star between instants t_{b} and t through

$$M_{\mathrm{R}}^{\mathrm{w}}(t_b, t) = \int_{t_b}^{t} X_{\mathrm{R}}^{\mathrm{s}}(t') \exp\left(-\frac{t-t'}{\tau_{\mathrm{R}}}\right) \mid \dot{M}(t') \mid \ \mathrm{d}t' \ . \qquad (1)$$

In this equation, $X^{\rm s}_{\rm R}(t')$ is the surface mass fraction of R at time t', $\mid \dot{M}(t') \mid$ is the instantaneous mass loss rate, and the radionuclide mean life $\tau_{\rm R}$ is defined from its half-life $t_{1/2}$(R) as $\tau_{\rm R} = t_{1/2}({\rm R})/\ln 2$ [Of course, through the stellar evolution calculations, time t can be univocally translated in terms of the remaining stellar mass $M(t)$ (see Fig. 1)]. Equation (1) can be trivially applied to stable nuclides by setting $\tau_{\rm R} \rightarrow \infty$.

Frequent use is made of times $t_{\rm b} = t_{\rm bZAMS}$ and $t = t_{\rm eWC}$ of start of the ZAMS and termination of the WC-WO phase, the latter time corresponding in practice to the pre-supernova stage. In the following, the total wind ejected mass $M^{\rm w}_{\rm R}(t_{\rm bZAMS}, t_{\rm eWC})$ of species R is simply denoted $M^{\rm w}_{\rm R}$. Of course, all the radionuclides and the neighbouring stable species of interest in this work (see Figs. 6–10) are not necessarily coeval in the WR ejecta at all evolutionary stages. More specifically, the H-burning ^{26}Al and ^{27}Al ashes are ejected at the WN stage (e.g. Prantzos et al. 1986; Meynet et al. 1996) along with the stable s-process nuclides assumed to be present in the material of the star at its birth. As these cannot be affected by any nuclear processing before the WC stage, it is considered that their relative yields before this evolutionary phase are in solar proportions, while their absolute yields just scale with metallicity Z as $Z/{\rm Z}_\odot$. These "economical" approximations appear to be accurate enough for our purpose. At the onset of the WC-WO phase, the WR wind starts carrying the s-process radionuclides and stable nuclides produced by the He-burning core. Some ^{27}Al may also continue to be ejected, in contrast to ^{26}Al, which is very quickly destroyed by (n,p) reactions in the course of central He burning (e.g. Prantzos et al. 1986; Meynet et al. 1996).

At this point, it has to be emphasized that not all the considered model stars are predicted to lose enough mass to go through a He-burning and s-process enriched WC-WO wind. More specifically, the adopted dependence of the mass loss rate on Z leads to the result that the considered 25, 40, and 60 M$_\odot$ model stars do not enter the WC-WO phase for the considered $Z \leq 0.02$, $Z \leq 0.004$ and $Z = 0.001$, respectively, while the 85 and 120 M$_\odot$ model stars do not reach the WC-WO stage for $Z = 0.04$. The subset of the considered model stars that indeed experience the WC-WO phase will be referred to in the following as the "WC star subset".

For illustration, Fig. 2 displays the evolution of $M^{\rm w}_{\rm R}(t_{\rm bWC}, t)$ for some radionuclides produced by the He-burning s-process in the 60 M$_\odot$ model star with $Z = 0.02$. The efficiency of the corresponding neutron capture process can be measured in terms of an "effective" neutron exposure $\tau_{\rm eff}(t)$ defined as

$$\tau_{\rm eff}(t) = \int_{t_{\rm bWC}}^{t} \langle\tau_{\rm n}(t')\rangle \mid \dot{M}(t') \mid {\rm d}t' \bigg/ \int_{t_{\rm bWC}}^{t} \mid \dot{M}(t') \mid {\rm d}t' \,, \qquad (2)$$

where

$$\langle\tau_{\rm n}(t)\rangle = \int_{t_{\rm bWC}}^{t} \left[\frac{1}{M_{\rm cc}(t')} \int_{0}^{M_{\rm cc}(t')} N_{\rm n}(t', m) v_{\rm T}(t', m)\, {\rm d}m\right] {\rm d}t'$$

is the neutron exposure averaged over the convective He-burning core whose mass at time t' is $M_{\rm cc}(t')$. In the latter expression, $N_{\rm n}$ represents the neutron number density and $v_{\rm T}$ the mean thermal velocity of the neutrons. The derived $\tau_{\rm eff}(t)$ are displayed in Fig. 3 for the 60 M$_\odot$ model star at the three metallicities Z for which it goes through the WC-WO phase. It is seen that they are much smaller than the average values τ_0 of the neutron irradiation commonly adopted in the $0.15 \lesssim \tau_0 \lesssim 0.30$ mb^{-1} range in parametric studies of the isotopic anomalies of s-process origin. In contrast, they are within the range $\tau \lesssim 0.01$ mb^{-1} considered by Arnould and Howard (1993) during most of the WC-WO evolution.

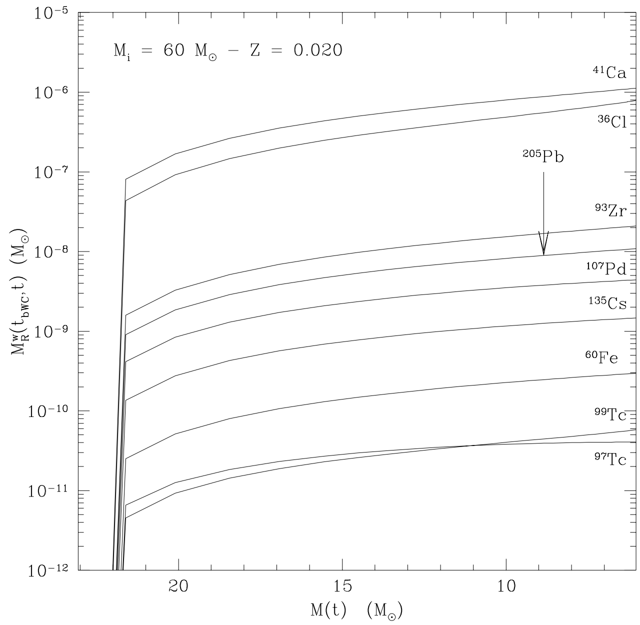

Fig. 2. Values of $M^{\rm w}_{\rm R}(t_{\rm bWC}, t)$ for some s-process radionuclides ejected by the wind of a $M_{\rm i}$ = 60 M$_\odot$ WR star with Z = 0.02 from the start of the WC phase ($t = t_{\rm bWC}$) up to time t at which the remaining stellar mass is $M(t)$. For $t \leq t_{\rm bWC}$, the WR wind is free from these radionuclides

4. Confrontation with observations

This section is mainly devoted to a comparison between our WR yield predictions and the abundances of s-process radionuclides in the early solar system inferred from the excesses in their daughter nuclei observed in meteoritic material. We will also briefly discuss the case of ^{26}Al. A more thorough discussion of the ^{26}Al yields from WR stars and of their implications for cosmochemistry and γ-ray line astronomy will be presented elsewhere.

4.1. The case of ^{107}Pd

As reviewed by Wasserburg (1985; see also Chen and Wasserburg 1990), this nucleus ($t_{1/2}$ = 6.5 10^6 y) provides the best documented case for the existence in the early solar system of a radionuclide that can be produced by the s-process (as it is not shielded by stable isobars from the r-process, it can of course also be synthesized by that mechanism). From the available data,

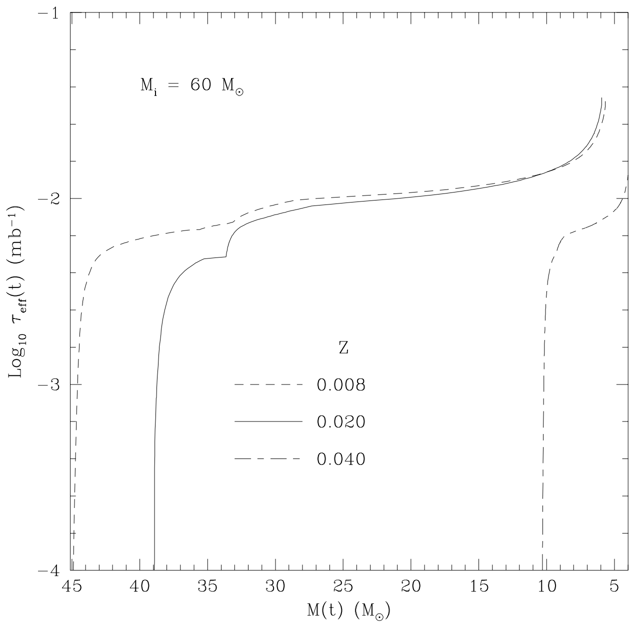

Fig. 3. Values of the effective neutron exposure $\tau_{\rm eff}(t)$ [Eq. (2)] versus the remaining mass $M(t)$ characterizing the s-process developing during the central He-burning phase of the $M_{\rm i}$ = 60 $M_\odot$ model star at the three considered metallicities Z for which it goes through the WC-WO phase

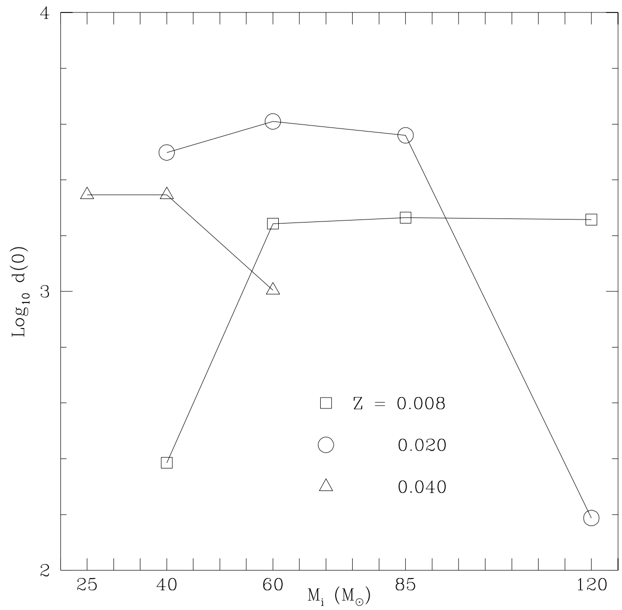

Fig. 4. Values of $d(0)$ [Eq. (3)] for the WC star subset limited to metallicities Z = 0.008, 0.02 and 0.04

it is inferred that $(^{107}{\rm Pd}/^{108}{\rm Pd})_0 \approx 2\,10^{-5}$ represents a "canonical" value of the abundance ratio at the start of the condensation of solar system solid bodies (in the following, the subscript 0 will always refer to that epoch).

In the simplified picture assuming that the ^{107}Pd present in the wind of a WR star at the end of its WC-WO phase can find its way into solar system solid bodies after a period Δ^* of free decay, the $(^{107}{\rm Pd}/^{108}{\rm Pd})_0 = 2\,10^{-5}$ ratio can be accounted for if a normalization ("dilution") factor d is applied to the value of the ^{107}Pd/^{108}Pd ratio calculated in the WR wind. The $d(0) \equiv d(\Delta^* = 0)$ values derived in the limit of no free decay period are presented in Fig. 4 for the WC star subset under the simplifying assumption of a complete mixing of the wind material ejected between the ZAMS and the end of the computed evolutionary sequences. Figure 4 indicates that $d(0)$ factors between about 10^3 and 10^4 are allowed for most of the displayed $Z \geq 0.008$ model stars. The dilution factors that have to be applied for $\Delta^* \neq 0$ can be trivially derived from $d(0)$ following

$$d(\Delta^*) = d(0)\ \exp(-\Delta^*/\tau_{^{107}{\rm Pd}})\ . \quad (3)$$

The assumption of thorough mixing of the entire material lost by stellar wind that is made in order to obtain the dilution factors displayed in Fig. 4 might be replaced by a scenario in which the complete mixing concerns the WC-WO wind only. In such an extreme case, which may have some astrophysical relevance (see Sect. 5), larger dilution factors, denoted $d_{\rm WC}(0)$, would be obtained, the mixing with pre-WC ^{107}Pd-free wind being suppressed. More specifically, $d_{\rm WC}$ values ranging from about 5000 to 32 000 are computed. They are found to be almost independent of $M_{\rm i}$ and to vary with Z following the approximate law $d_{\rm WC}(0) = 4.92\,10^6 Z^2 + 5.05\,10^5 Z + 837.5$.

From the dilution factors just discussed, one can try estimating if indeed there is any chance for a contamination of the protosolar nebula with isotopically anomalous WR wind material, and in particular with ^{107}Pd. From a qualitative discussion of this highly complex question presented in Sect. 5, we come to the conclusion that such a possibility is not utterly farfetched, and that one or several WR stars with $M_{\rm i}$ in a broad range of values could account for the entire amount of ^{107}Pd that has been injected live into the early solar system (either in the form of gas or grains). It is also seen that large ^{107}Pd yields are obtained for a wide variety of metallicities. Of course, we do not imply by this statement that WR stars with Z vastly different from $Z_\odot$ can have contributed to live radionuclides in the early solar system, even if stars with different Z are known to be coeval in the galactic disk. In fact, data are presented for the whole Z range mainly for the sake of completeness, and as a help to derive by interpolation the dilution factors appropriate to Z slightly different from $Z_\odot$.

The dilution factors deduced from the ^{107}Pd yields will be applied to the other radionuclides to be discussed below, thus neglecting any possible fractionation effects.

4.2. The case of ^{60}Fe

The presence of live ^{60}Fe ($t_{1/2}$ = 1.5 10^6 y) in the early solar system has been deduced from the analysis of various eucrites (Shukolyukov and Lugmair 1993a,b). These studies, complemented with good quality ^{53}Mn – ^{53}Cr isochrones lead Lugmair et al. (1995) to conclude that $(^{60}{\rm Fe}/^{56}{\rm Fe})_0$ possibly ranges be-

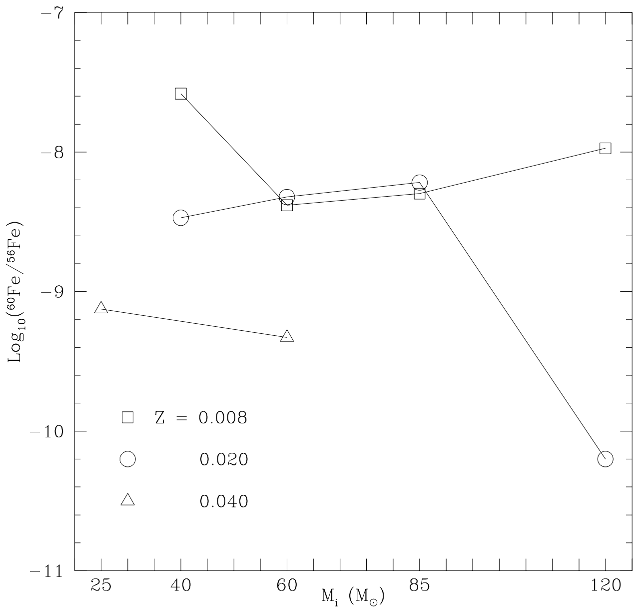

Fig. 5. Values of ^{60}Fe/^{56}Fe at the end of the WC-WO phase for the WC star subset limited to metallicities Z = 0.008, 0.02 and 0.04

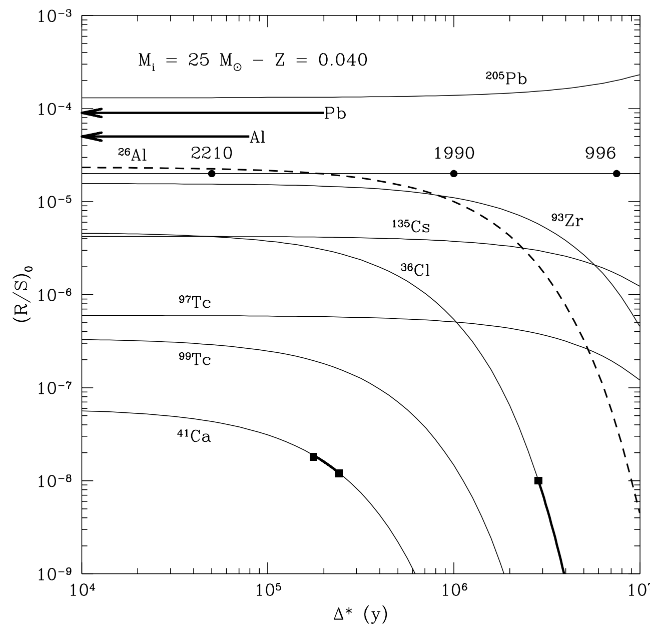

Fig. 6. Abundance ratios $(R/S)_0$ of various radionuclides R relative to stable neighbours S versus Δ^* (see main text) for the 25 $M_\odot$ model star with Z = 0.04 (for the other considered metallicities, the 25 $M_\odot$ star does not experience the WC-WO phase). The curves labelled ^{26}Al, ^{36}Cl, ^{41}Ca, ^{93}Zr, ^{97}Tc, ^{99}Tc, ^{135}Cs and ^{205}Pb refer to the following R/S ratios: ^{26}Al/^{27}Al, ^{36}Cl/^{37}Cl, ^{41}Ca/^{40}Ca, ^{93}Zr/^{92}Zr, ^{97}Tc/^{100}Ru, ^{99}Tc/^{100}Ru, ^{135}Cs/^{133}Cs and ^{205}Pb/^{204}Pb. All the displayed ratios are normalized to $(^{107}\mathrm{Pd}/^{108}\mathrm{Pd})_0 = 2\,10^{-5}$ 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^*. Short dashes for the ^{26}Al curve indicate that the radionuclide loads the WN wind only, while solid lines represent radionuclides contaminating the WC-WO wind. Other available experimental data are illustrated. They are adopted from MacPherson et al. (1995) for Al and Huey & Kohman (1972) for Pb (thick arrows labelled Al and Pb, respectively), Srinivasan et al. (1994) for Ca and Jordan & Pernicka (1981) for Cl (solid squares and thick lines)

tween their measured lower limit of $4\,10^{-9}$ and an estimated upper limit of $6\,10^{-8}$, with a most probable value of $1.6\,10^{-8}$.

Figure 5 shows that the abundance ratio ^{60}Fe/^{56}Fe in the WR winds at the end of the WC-WO phase is at most of the order of $(1-2)\,10^{-8}$, that is at most $(2.5-5)$ times only the measured $(^{60}\mathrm{Fe}/^{56}\mathrm{Fe})_0$ lower limit. In such conditions, the application of the dilution factors derived from the ^{107}Pd yields (Fig. 4) would bring the predicted values of the $(^{60}\mathrm{Fe}/^{56}\mathrm{Fe})_0$ ratio well below the range proposed by Lugmair et al. (1995) (in fact, the calculated values of this ratio would lie out of scale in Figs. 6 - 10 of Sect. 4.3). It is thus concluded that the solar system ^{60}Fe cannot have a WR origin, at least if the pre-explosion phase only is considered. The ensuing supernova might well bring the necessary ^{60}Fe complement required to account for the meteoritic observations (other types of supernovae could also enrich the interstellar medium with ^{60}Fe; see e.g. Timmes et al. 1995).

4.3. Other radionuclides of possible s-process origin

Other radionuclides of potential cosmochemical interest could be ejected by the WC-WO wind of the considered stars. The situation is summarized in Figs. 6–10 for the models of the WC star subset with metallicities that are the closest to $Z_\odot$ (Z = 0.008, 0.02 and 0.04), and for which $d(0) \gtrsim 10^3$ (see Fig. 4). These restrictions are adopted for the sake of conciseness only (see Sect. 4.1 for a brief discussion of the possibility for $Z \neq Z_\odot$ stars to inject radionuclides in the protosolar nebula).

Displayed in Figs. 6–10 are the values of the ratio $(R/S)_0$ of the mass of a radionuclide R to the mass of a neighbouring stable nuclide S at the start of condensation in the solar system. They are derived

1. from the masses M_R^w and M_S^w [see Eq. (1)];
2. by allowing R to decay freely for a period Δ^* assumed to separate the end of the nucleosynthesis episode from the start of condensation in the solar system;
3. by applying the dilution factors $d(\Delta^*)$ derived from ^{107}Pd, as discussed in Sect. 4.1, so that the $(^{107}\mathrm{Pd}/^{108}\mathrm{Pd})_0$ curve is just a horizontal line with ordinate $2\,10^{-5}$. In each of the Figs. 6–10, three values of $d(\Delta^*)$ label the Pd line.

Let us note in particular from Figs. 6–10 that

(1) the WC-WO wind could carry quite significant amounts of ^{41}Ca ($t_{1/2}$ = 10^5 y). Srinivasan et al. (1994) have derived a value $(^{41}\mathrm{Ca}/^{40}\mathrm{Ca})_0 = (1.5 \pm 0.3)\,10^{-8}$ in the Efremovka CAIs at the time of their formation. This evidence for the existence of ^{41}Ca live in the early solar system is quite crucial in view of its relatively short half-life.

Roughly speaking, (i) the calculated normalized $(^{41}\mathrm{Ca}/^{40}\mathrm{Ca})_0$ ratios at a given Δ^* have a tendency to decrease with increasing M_i and Z (there are a few exceptions to this statement), and (ii) the $(^{41}\mathrm{Ca}/^{40}\mathrm{Ca})_0 \approx 10^{-8}$ ratio can be ac-

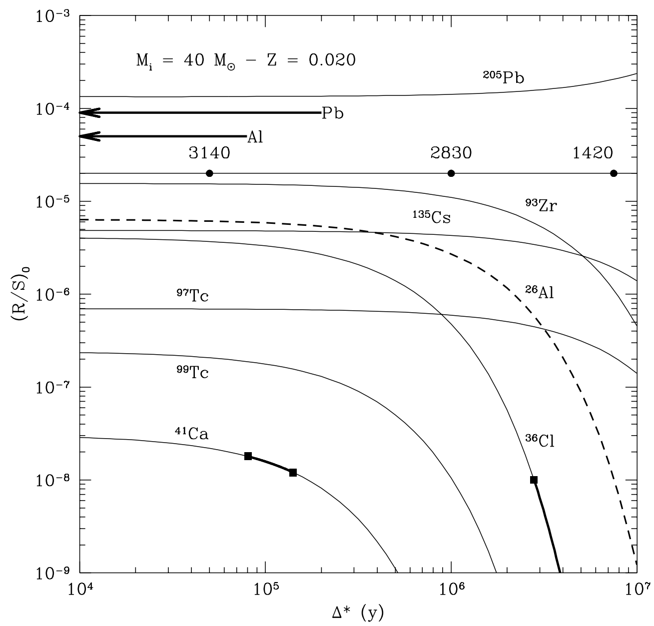

Fig. 7. Same as Fig. 6, but for $M_{\rm i} = 40\,{\rm M}_\odot$ and $Z = 0.02$. The $Z = 0.04$ model star does not go through the WC-WO phase, while the $Z = 0.008$ case of the WC subset is not represented in view of the correspondingly low dilution factor $d(0)$ (Fig. 4)

counted for in the approximate range $\Delta^* \approx (1-5)\,10^5$ y for the displayed stars, except for the $60\,{\rm M}_\odot$ with $Z = 0.04$, for which the $(^{41}{\rm Ca}/^{40}{\rm Ca})_0$ ratio is predicted to be lower than 10^{-8} even in the limit $\Delta^* = 0$;

(2) with a few exceptions, the predicted normalized $(^{36}{\rm Cl}/^{37}{\rm Cl})_0$ ratios are seen to decrease with increasing Z for a given Δ^*, while they remain roughly constant or decrease slightly with increasing $M_{\rm i}$. The amount of ^{36}Cl in the WC-WO winds could account for the very uncertain limit $(^{36}{\rm Cl}/^{37}{\rm Cl})_0 \lesssim 10^{-8}$ (Jordan and Pernicka 1981) for $\Delta^* \gtrsim (2-3)\,10^6$ y, roughly independent of mass and metallicity;

(3) our calculations predict that ^{97}Tc and ^{99}Tc are carried by the WC-WO winds. Their decay might lead to meteoritic excesses of Mo and Ru, respectively. It may look surprising that some ^{97}Tc can emerge from a neutron capture process, while it is a neutron-deficient isotope classically attributed to the p-process. Its production in the WR stars results in fact from the transformation of the assumed initial (solar) ^{96}Ru amount by $^{96}{\rm Ru}\,({\rm n}\,,\gamma)\,^{97}{\rm Ru}\,(\beta^+)^{97}{\rm Tc}$. The derived neutron irradiation is sufficient for such a chain to develop, but low enough to not destroy all the ^{97}Tc produced in such a way. In its turn, this weak ^{97}Tc destruction implies in fact an insignificant ^{98}Tc production.

It is seen that $(^{97}{\rm Tc}/^{100}{\rm Ru})_0$ is larger or smaller than $(^{99}{\rm Tc}/^{100}{\rm Ru})_0$ for Δ^* values lower than the half-lives of the two considered Tc isotopes. This results from the fact that the former ratio increases with increasing Z, while the reverse is observed for the latter one. In both cases, no clear trend emerges for varying $M_{\rm i}$ at given Z. In all cases, ^{99}Tc is less abundant than ^{97}Tc for $\Delta^* \gtrsim 10^5 - 10^6$ y. This of course relates directly to the fact that ^{97}Tc is longer-lived than ^{99}Tc.

A possible excess of ^{99}Ru has been reported by Yin et al. (1992) in a magnetic fraction of the Moralinga carbonaceous chondrite, and is tentatively attributed to the presence of live ^{99}Tc in the early solar system. On the other hand, no unambiguous trace of the possible existence of live ^{97}Tc has been discovered to-date from measurements of the Mo isotopic composition (Qi Lu & Masuda 1991, 1992). A further search, and the confrontation of its (either positive, or negative) results with our theoretical expectations regarding the loading of WR winds with Tc would be very interesting;

(4) normalized $(^{205}{\rm Pb}/^{204}{\rm Pb})_0$ ratios between 10^{-4} and 10^{-3} are obtained, in agreement with earlier predictions by Arnould and Prantzos (1986) and Arnould (1993). Those values exceed largely the experimental upper limit of $9\,10^{-5}$ (Huey and Kohman 1972).

The particular nuclear physics, astrophysics and, possibly, cosmochemistry interest of the ^{205}Pb–^{205}Tl pair has been discussed in detail elsewhere (Yokoi et al. 1985). Let us just mention here that it might very usefully complement other radionuclide data, as ^{205}Pb might be a pure s-process nucleus. In addition, it has been shown by Yokoi et al. (1985) that other studies (e.g. Blake and Schramm 1975) have underestimated the s-process ^{205}Pb/^{204}Pb production ratio, in particular as a result of a drastic underestimate of the ^{205}Pb effective lifetime in certain stellar conditions. This relates to the neglect of the ^{205}Tl bound-state β-decay, which can effectively hinder the ^{205}Pb destruction in a quite large variety of astrophysical environments. This work reinforces the view (Yokoi et al. 1985) that the ^{205}Pb–^{205}Tl pair is not necessarily a farfetched s-process chronometer, and gives more credit to a plea for a renewed search for extinct ^{205}Pb in meteorites (see Chen and Wasserburg 1994);

(5) other short-lived nuclides are present in more or less large amounts in the WC-WO winds, like ^{93}Zr or ^{135}Cs. However, the decay of the first one to ^{93}Nb cannot lead to observable isotopic anomalies in view of the monoisotopic nature of Nb. As far as ^{135}Cs is concerned, the normalized $(^{135}{\rm Cs}/^{133}{\rm Cs})_0$ ratio is found to lie approximately between 10^{-6} and 10^{-5} for $\Delta^* \lesssim 10^7$ y for stars of the WC subset with $Z \geq 0.008$, except for the $40\,{\rm M}_\odot$ case with $Z = 0.008$, where $(^{135}{\rm Cs}/^{133}{\rm Cs})_0 \lesssim 10^{-6}$. At this point, it appears premature to try confronting these predictions with the somewhat confusing experimental searches for the signature of the ^{135}Cs decay in the Ba isotopic composition (McCulloch & Wasserburg 1978, Harper et al. 1991, 1992)

As far as ^{182}Hf is concerned, it is found that the normalized $(^{182}{\rm Hf}/^{180}{\rm Hf})_0$ ratio never exceeds a value of about 10^{-11} for the $Z \geq 0.008$ stars of the WC subset except in the $Z = 0.008$ $40\,{\rm M}_\odot$ case, where a ratio of about 10^{-10} is reached. At present, there is just an observational hint for the presence of ^{182}Hf in the early solar system (Harper and Jacobsen 1994).

4.4. *The case of* ^{26}Al

It is widely recognized nowadays that the radionuclide ^{26}Al ($t_{1/2}$ = $7.3\,10^5$ y) is of crucial importance in γ-ray astronomy

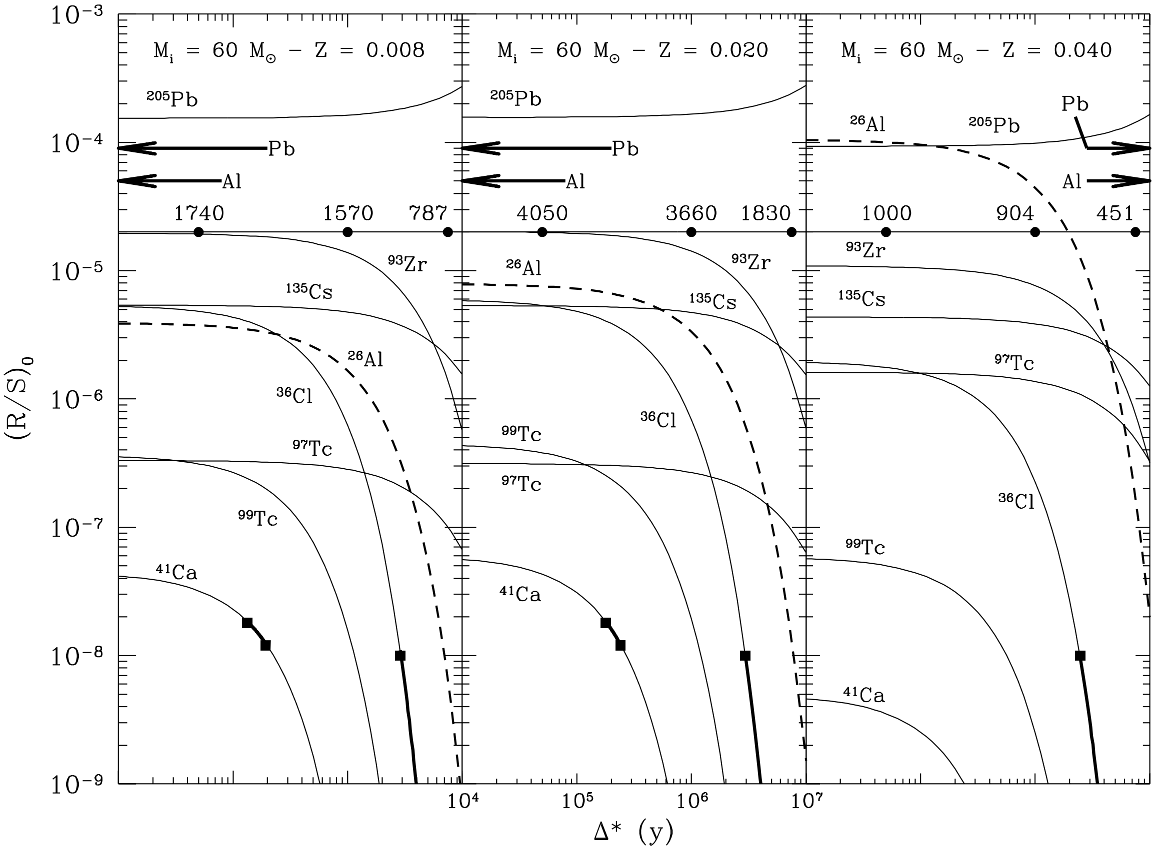

Fig. 8. Same as Fig. 6, but for $M_{\rm i} = 60\,{\rm M}_\odot$. In the $Z = 0.04$ case, the ^{41}Ca curve lies below the Srinivasan et al. (1994) experimental values which are not displayed

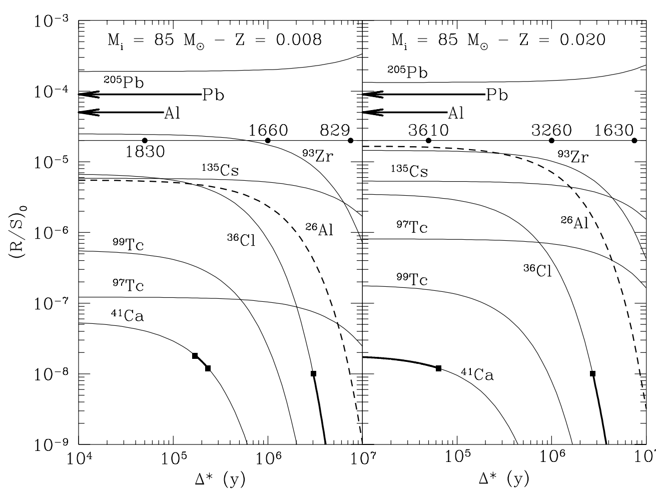

Fig. 9. Same as Fig. 6, but for $M_{\rm i} = 85\,{\rm M}_\odot$. The $Z = 0.04$ star does not go through the WC-WO phase

and cosmochemistry. There is now ample observational evidence that ^{26}Al has decayed in situ in various meteoritic inclusions (MacPherson et al. 1995), as well as in identified single grains of likely circumstellar origin (e.g. Anders and Zinner 1993).

Various potential ^{26}Al production sites have been suggested and studied in more or less great detail (e. g. Prantzos and Diehl 1996, and references therein). In particular, WR stars have been considered as possible ^{26}Al contaminating agents of at least some of the meteoritic material mentioned above (Arnould and Prantzos 1986, Meynet and Arnould 1993).

Figures 6–10 indicate that the normalized $(^{26}{\rm Al}/^{27}{\rm Al})_0$ ratios increase with increasing $M_{\rm i}$ and Z, and can reach the canonical value of $5\,10^{-5}$ for $M_{\rm i} \gtrsim 60\,{\rm M}_\odot$ stars with high enough metallicity. At this point, it has to be reminded that this conclusion is reached when the same dilution factors are adopted for Al and Pd. This might not be fully adequate from a physico-chemical point of view. This approximation might also break down because, as already stressed above, ^{26}Al loads the WN wind, while the other considered radionuclides are ejected at the WC-WO phase only.

5. How now: a contamination of the solar system by WR winds ?

The detailed yield predictions presented above raise the question of the probability of a significant contamination of the protosolar nebula with WR gas or grains of anomalous composition, and especially with the radionuclides considered in this work. Quantitative statements about this question would of course ne-

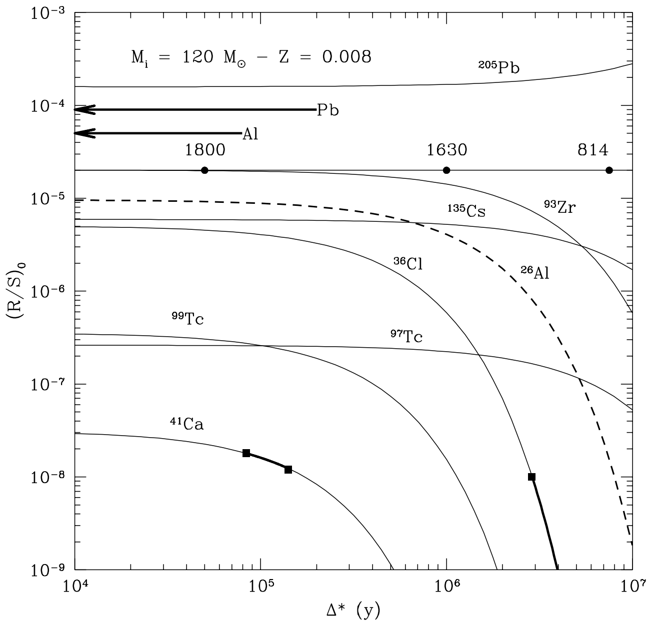

Fig. 10. Same as Fig. 6, but for $M_i = 120\,M_\odot$. The $Z = 0.04$ model star does not go through the WC-WO phase, while the $Z = 0.02$ case of the WC subset is not represented in view of the correspondingly low dilution factor $d(0)$ (Fig. 4)

cessitate the knowledge of the details of the history of the material from its wind ejection by WR stars up to its inclusion into the forming solar system. Clearly, most aspects of such a scenario, if it ever developed, are unknown, and this paper certainly does not claim unravelling its many mysteries. However, one may at least try evaluating in a highly qualitative way the astrophysical plausibility of the contaminating role of WR stars.

This question represents obviously a particular aspect of the much more general problem of triggered star formation. As extensively reviewed by Elmegreen (1992), there is now mounting and compelling observational evidence that the overpressures exerted on the surroundings of massive stars by their *radiation* and/or *winds* can induce the formation of stars, sometimes of low mass, where it would not have occurred otherwise, or at least speed up star formation where it would otherwise have occurred at a slower rate. These observations have been complemented with much theoretical effort aimed at identifying the most crucial physical quantities that could influence the success or failure of triggered star formation, and at evaluating the relevant ranges of values of these quantities.

From these many observational and theoretical efforts, the idea emerges that triggered star formation can occur in a very large variety of situations. In particular, it is seen to take place at relatively small astronomical distance scales, and to involve rather small and low-mass clumps of material. More specifically, stars can form in isolated small globules made of dense neutral gas and dust squeezed from all sides by the hydrogen-ionized gas of young and compact HII regions in which they are embedded. These HII regions extend over distances that can vary from a few parsecs (pc), or even less in the case of short-lived ultracompact HII regions, to some tens of pc from the massive ionizing star(s). The squeezed globules may have typical dimensions ranging from a fraction of a pc to more than one pc, and masses from less than 1 $M_\odot$ to tens or hundreds of solar masses. The edges of HII regions often exhibit numerous small-scale (typically of the order of parsecs) bulbs and protrusions with highly varied shapes. These clumps most probably result from the lateral overpressure exerted by the expanding HII region on its neutral surroundings, in contrast to the overall squeezing of individual globules mentioned above. Numerous observations suggest that stars are forming in these locations. They might even be the sites of small-scale sequential low-mass star formation (Sugitani et al. 1995). In addition to the squeezing of globules inside or at the edges of HII regions, the compression of isolated clouds can also occur outside these ionized zones, in regions exposed to various types of shocks.

At this point, it is important to emphasize that the star forming globules referred to above may be preexisting structures, or cloudlets resulting from various types of instabilities fragmenting filaments, sheets or shells. As a consequence, the material comprised in globules at their stage of star formation may be of genuine interstellar origin, but may also be in variable proportions matter lost by the winds of the massive stars responsible for the star formation triggering.

Another important aspect of the process of star birth from the globules considered above concerns the typical formation timescales. These may be as short as the dynamical collapse time of globules (which can be of the order of 10^4 y or shorter), while a sequence of formation of multiple low-mass stars may be achieved within a few 10^5 y (Sugitani et al. 1995). Situations have been identified in which the sequential star formation process is about ten times longer, that is of the order of massive star evolution lifetimes.

In relation with the question of the possible contamination of the solar system with radionuclides originating from WR stars, several specific comments complementing the more general considerations presented above are in order:

(1) it has to be acknowledged that the precise role played in the star formation process by the WR phase of massive stars has, as far as we know, never been singled out. However, it can be imagined that WR stars can at least bring some touch to the triggering process. Such a possibility is not contradicted by the typical timescales involved in this process (see above);

(2) even if the ability of WR stars to contaminate the material going into forming stars does not in principle tightly relate to the role they play in such a triggering, it is reasonable to consider that the contamination is made more likely or easier if indeed WR wind ejection and star birth are connected in some way. Anyhow, it is quite clear that the WR wind has to reach the globule material in due time for (i) enough radionuclides to survive, and (ii) part at least of the WR anomalous matter to have the opportunity to be engulfed in the forming solar-system type structure;

(3) obviously, question 2(i) directly relates to the travel time of the wind from a WR star to the star forming globule. Quite

clearly also, small scale or some intermediate scale star formation triggering (in the terminology of e.g. Elmegreen 1992) are the most appropriate for having travel times shorter than, or at least commensurable with the lifetimes of the radionuclides of interest. A rough estimate of likely travel times may be obtained as follows. Let us assume that globules that could possibly be compressed to solar-system-like structures could not have been closer to the WR star than the inner edges of the neutral hydrogen shells (referred to as HI shells) that are observed to enclose the HII regions of some WR stars of the WN and WC subtypes (e.g. Nichols 1995 for a review and references). The observed HI shells are often barrel-shaped, with semi-major axes ranging from about 10 to 50 pc, the semi-minor axes being about twice shorter. Quite remarkably, the embedded WR stars are always located off-centre, their closest distance to the HI shell being possibly as small as about 5 pc (e.g. Arnal 1992; see also below). It is considered probable that all WR stars exhibit such HI shell structures.

In such conditions, assuming that the WR wind expands freely, and adopting a conservative wind velocity of 1000 km/s, it would take about 5 10^4 y for the ejected material to reach the most distant inner edges of the HI shell, assuming a central location of the WR star. Of course, the contamination of the portions of the HI shell located closest to the off-centre WR star would be even quicker. This makes plausible that the WR wind could reach star-forming globules in timescales that are commensurable with, and possibly even shorter than the mean lives of the radionuclides considered in this work. This would especially be the case if squeezed globules located inside the cavity bounded by the HI shell could survive the erosion by the radiation and wind of the massive star up to the WR contamination (it has to be reminded that neutral blobs of material are observed *inside* some HII regions associated with massive stars);

(4) we now briefly consider question 2(ii). That live radionuclides have time to reach a nascent solar system structure from their WR production site (see 3) is of course only a necessary condition for the possibility of contamination. An additional constraint is that the radionuclide-loaded material must arrive in time for part of it at least to be engulfed in the material that will eventually be comprised in the solar system. The possibility of meeting this constraint does not seem utterly farfetched when it is reminded (see above) that typical lifetimes (from about several times 10^5 to some 10^6 y) for sequential star formation may be of the order of the lifetimes of the radionuclides considered in this work.

All in all, we thus conclude that astrophysically plausible values of Δ^* could well lie in the $10^4 \lesssim \Delta^* \lesssim 10^7$ y range adopted in Figs. 6–10, Δ^* being interpreted in the triggered star formation context just sketched above as the travel time of the WR wind from the star to a globule, plus the time it takes for part of the wind to be trapped in the collapsing part of the globule and ultimately in forming solids;

(5) considering from the above discussion that radionuclides can indeed be injected live in the forming solar system, it remains to be seen if the level of contamination is sufficient to account for the observations. In order to do this, let us assume the simplest possible situation of a spherically symmetric WR wind hitting the pre-solar-system globule with effective linear dimension $L_{\rm glob}$ located D pc away from the contaminating WR star. In such a simple geometry, the dilution factor d [Eq. (3)] relates to $L_{\rm glob}$ and D by

$$d = \frac{4D^2}{L_{\rm glob}^2} \times \frac{M_{^{108}{\rm Pd}}({\rm glob})}{M^{\rm w}_{^{108}{\rm Pd}}} \quad , \tag{4}$$

where $M_{^{108}{\rm Pd}}$(glob) and $M^{\rm w}_{^{108}{\rm Pd}}$ are the mass of ^{108}Pd initially present in the solar-system forming globule and its mass ejected in the wind of the WR star from its ZAMS until the end of its WC phase.

In order to analyze qualitatively the implications of this relation, let us assume that the globule has initially a solar ^{108}Pd mass fraction, so that $M_{^{108}{\rm Pd}}({\rm glob}) \approx 10^{-9} M({\rm glob})$, where M(glob) is the mass of the solar system forming globule. In addition, it is considered that the globule is spherical, and has a uniform distribution of material made of (mostly molecular) hydrogen with a typical number density $n_{\rm H}$. On the other hand, our stellar model calculations indicate that $M^{\rm w}_{^{108}{\rm Pd}} \approx 10^{-7}\,{\rm M}_\odot$ within a factor of about 2. If we impose that d = 2 10^3, which is, as discussed above, a rough typical dilution factor needed for most of the considered stellar yields to account for the right level of ^{107}Pd contamination, Eq. (4) translates into $D^2 L_{\rm glob}$ = 4 $10^6/n_{\rm H}$ if both D and $L_{\rm glob}$ are expressed in pc, and $n_{\rm H}$ in cm^{-3}.

In order to explore the extent to which this constraint can be met in astrophysically plausible situations, let us adopt first $n_{\rm H}$ = 4 10^3, which appears to be a typical average value for isolated globules (e.g. Clemens et al. 1991). Imposing $D < 50$ pc in order to avoid travel times for the radionuclides exceeding their lifetimes (see 3), we are led to $L_{\rm glob} > 0.4$ pc, corresponding to $M_{\rm glob} > 3\,{\rm M}_\odot$. These values are fully compatible with the characteristic properties of these isolated globules (e.g. Clemens et al. 1991). In the case of globules squeezed laterally at the edges of HII regions (see above), typical $n_{\rm H}$ values as high as about 5 10^4 are reported (e.g. Sugitani and Ogura 1994). In such conditions, it is just required that $L_{\rm glob} > 0.03$ pc if $D < 50$ pc, corresponding to $M_{\rm glob} > 0.02\,{\rm M}_\odot$. These values are again compatible with the observed properties of these dense cloudlets (e. g. Sugitani and Ogura 1994).

In conclusion, astrophysically plausible situations may be found in which the levels of WR wind contamination are of the order of magnitude of those required by the meteoritic radionuclide data. Of course, this statement derives from a highly simplistic calculation that neglects the very many intricacies of the more realistic situations demonstrated by observation and suggested by numerical simulations.

Among these intricacies, one has certainly to emphasize the mounting observational evidence that the winds of at least certain WR stars are far from spherically symmetric and density homogeneous, and exhibit instead bipolar structures, blobs or clumps. This observed high complexity of the WR circumstellar environment is supported by recent multi-dimensional hydrodynamic simulations of the winds blowing *at the centre* of the bubble created by the material ejected by the WR progenitors (e. g. Garcia-Segura et al. 1996, and references therein). Special dynamic effects are also predicted in the frequently observed case of WR stars moving with more or less high speeds away from the centre of their progenitor bubbles (e. g. Brighenti and D'Ercole 1995a,b). In some cases, these displacements might be rapid enough and the evolutionary time scales long enough for the WR stars to blow their winds *outside* of their progenitor bubbles. As emphasized by Brighenti and D'Ercole (1995b), this type of scenario might also have a profound impact on the *composition* of the nebulae surrouding the WR stars, which might be made of purer WR ejecta than in the non-moving WR counterpart. In other words, the dilution factors of relevance in such a situation might be intermediate between the d and $d_{\rm WC}$ factors introduced in Sect. 4. The proximity of other massive stars encountered in binary systems or in associations might also have a more or less profound influence on the dynamics and composition of the WR star environments (e. g. Stevens and Pollock 1994 for the modelling of a WR wind interacting with the ejecta of a massive companion in a binary system). The presence of pre-existing interstellar medium density inhomogeneities would certainly add new dimensions to the complexity of the problem.

The resulting highly complex WR wind structure could not only relax some of the dilution constraints obtained above on grounds of purely spherically and homogeneous winds, but it might also help mixing the WR wind material into the protosolar nebula.[3]

Finally, it has to be stressed that a significant population of grains are observed to form either continuously or episodically from the ejecta of WC stars of various subtypes (e. g. Williams 1995 for a review and references) so close to the stars that a large dilution of the WR ejecta with genuine interstellar material can be avoided. This grain population might provide an efficient agent of contamination with WR material of forming solar-system types of structures.

Episodic grain formation might in fact be of special interest in relation with isotopically anomalous grains of circumstellar origin found in meteorites. This formation is generally interpreted as the result of the interaction of the winds of WR stars and of their companion stars in binary systems (see e. g. Usov 1991 for some theoretical considerations). One might thus speculate that the shock between WC carbon-rich winds and the oxygen-rich ejecta from O-type stars might lead to the development of a grain population with special morphological and compositional characteristics.

6. Conclusions

This paper presents new predictions for the non-explosive yields of long-lived radionuclides of cosmochemical interest. They are derived from improved models for single massive stars in a wide range of initial masses and metallicities. The main results may be briefly summarized as follows:

(1) in absence of any chemical fractionation between the relevant elements, ^{26}Al, ^{41}Ca and ^{107}Pd can be produced by a variety of WR stars with different initial masses and compositions at a *relative* level compatible with the meteoritic observations. In contrast, too little ^{60}Fe is synthesized. A more or less large amount 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 relevant observations.

It has to be remarked that these 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 contribution possibly exhibits several interesting features:

(a) it might well be concomitant with the pre-explosive contamination of the forming structures of the solar system type. For example, Garcia-Segura et al. (1996) envision situations in which the WR material might hit the interstellar medium at the limit of WR progenitor bubble (and thus a region of potential star formation, in the views of the simple scenario discussed in Sect. 5) roughly at the time of the WR explosion;

(b) the explosively ejected contaminating material might well be enriched with products of the s-process that have not been carried by the pre-explosive wind, at least if some s-nuclides are able to survive the explosion. This s-process-enriched supernova material, if any, is expected to have experienced a much stronger neutron irradiation than the s-process-enriched wind. This relates to the fact that the ^{22}Ne$(\alpha,n)^{25}$Mg neutron producer acts mainly in the core close to the end of He burning, that is at a time when the material is locked in the pre-supernova structure. It remains for example to be seen if a non negligible amount of s-process produced ^{60}Fe could survive the supernova and be ejected explosively;

(c) the supernova ejecta could bring its share of radionuclides of non s-process origin, and in particular of ^{53}Mn, ^{60}Fe, ^{92}Nb, ^{129}I, ^{146}Sm, ^{182}Hf, or ^{244}Pu.

One has also to acknowledge that our conclusions put 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);

(2) the use of a simplistic scenario suggests that astrophysically plausible situations might be encountered such that radionuclides ejected by WR winds could indeed contaminate the forming solar system at an *absolute* level compatible with the observations;

(3) observations and models demonstrate that the interaction of WR stars with their surroundings is of high complexity. These complications should obviously have to be considered in order to reject or confirm the qualitative conclusion drawn above that WR stars could indeed be viable candidates for the contamination of forming solar system-like structures with isotopically anomalous material (in the form of gas or grains), and in particular with radionuclides in live form. Concomitantly, the possible role of WR stars, either isolated or in OB associations, in the triggering of the formation of some stars, and especially of low-mass stars, should have to be scrutinized.

[3] Arnould and Nørgaard (1978) have already emphasized that the contamination of the proto-solar nebula with isotopically anomalous material from supernovae might be eased if their ejecta contains density inhomogeneities, especially in the form of fast moving knots that are observed in certain remnants.

Finally, one has to recall that other astrophysical sites than WR stars are viable candidates for the contamination of the forming solar system with a more or less large variety of short-lived radionuclides. All of the proposed origins have their shortcomings and difficulties. In fact, a grand scenario involving a variety of them might be required. A necessary step in the building-up of such a scenario is to predict as reliably as possible the yields from all the individual sources. This paper is just trying to take this step in the case of the WR stars.

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