Solar r-process-constrained actinide production in neutrino-driven winds of supernovae

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ABSTRACT
Long-lived radioactive nuclei play an important role as nucleo-cosmochronometers and as cosmic tracers of nucleosynthetic source activity. In particular nuclei in the actinide region like thorium, uranium, and plutonium can testify to the enrichment of an environment by the still enigmatic astrophysical sources that are responsible for the production of neutron-rich nuclei by the rapid neutron-capture process (r-process). Supernovae and merging neutron-star (NS) or NS-black hole binaries are considered as most likely sources of the r-nuclei. But arguments in favour of one or the other or both are indirect and make use of assumptions; they are based on theoretical models with remaining simplifications and shortcomings. An unambiguous observational determination of a production event is still missing. In order to facilitate searches in this direction, e.g. by looking for radioactive tracers in stellar envelopes, the interstellar medium or terrestrial reservoirs, we provide improved theoretical estimates and corresponding uncertainty ranges for the actinide production ($^{232}$Th, $^{235}$U, $^{236}$U, $^{238}$U, $^{237}$Np, $^{244}$Pu, and $^{247}$Cm) in neutrino-driven winds of core-collapse supernovae. Since state-of-the-art supernova models do not yield r-process viable conditions — but still lack, for example, the effects of strong magnetic fields — we base our investigation on a simple analytical, Newtonian, adiabatic and steady-state wind model and consider the superposition of a large number of contributing components, whose nucleosynthesis-relevant parameters (mass weight, entropy, expansion time scale, and neutron excess) are constrained by the assumption that the integrated wind nucleosynthesis closely reproduces the solar system distribution of r-process elements. We also test the influence of uncertain nuclear physics.

Key words: nuclear reactions, nucleosynthesis, abundances – supernovae: general

1 INTRODUCTION
Actinides play an important role in astrophysics in different ways. First, the use of $^{232}$Th, $^{235}$U and $^{238}$U to estimate astrophysical ages has a long history, a milestone of which is the much celebrated piece of work of Fowler & Hoyle (1960). For long, the field of nucleo-cosmochronology that emerged from this paper has been aiming at the determination of the age $T_{\text{nuc}}$ of the nuclides from abundances in the material making up the bulk of the solar system. The astrophysical importance of Th and U was enhanced further with the observation of Th and U in some very metal-poor stars (Sneden et al. 1996; Cayrel et al. 2001). These measurements raised the hope of a possible nuclear-based evaluation of the age of individual stars other than the Sun.

Additional recent observational advances have triggered substantial interest in other actinides that are shorter-lived than Th and U. This comes about following the measurement of the Galactic Cosmic Ray (GCR) abundances of the $Z > 70$ elements, including the actinides, with unprecedented resolution, using the Trek detector (Westphal et al. 1998). Further significant progress is expected by the determination of the GCR abundances of the actinides Th, U, Pu and Cm both relative to each other and relative to the Pt-group of elements. Precise abundance measurements of this type would yield an estimate of the time elapsed between the nucleosynthesis of the GCR actinides and their acceleration to GCR energies (the GCR actinide propagation time after acceleration is very short, i.e. of the order of 2 My). Hence, they would help determining whether GCRs were accelerated out of fresh ejecta of the astrophysical r-element sources (supernovae or neutron-star mergers), superbubble material, or old, well-mixed galactic material.

Also attempts to measure the $^{244}$Pu content of the local interstellar medium should be mentioned here. Such mea-
measurements may allow for conclusions on the frequency of the astrophysical events producing actinides. At present, this can be done through the analysis of dust grains of identified interstellar origin recovered in deep-sea reservoirs (sediments and FeMn crusts; e.g. Paul et al. 2001; Wallner et al. 2015) and by the recovery of 60Fe incorporated in fossil biogenic samples (Bishop & Egl 2011; Ludwig et al. 2016; Witzel 2013). Marine sediments were also analysed for a 244Pu signal associated with measurements of 60Fe in a ferromanganese crust (Wallner et al. 2004; Raisbeck et al. 2007), which has been interpreted as product of a supernova close to the solar system about 2.2 My ago (Knie et al. 1999; 2004; Fitoussi et al. 2008).

For all these reasons, there is an obvious need to provide detailed theoretical estimates of the possible stellar production of actinides with half-lives in excess of typically 10^6 y. Most importantly, the uncertainties in these predicted abundances should be evaluated as well. While the actinides are clearly produced by the rapid neutron-capture process (or r-process) of stellar nucleosynthesis, the site(s) of this nucleosynthesis process have not been unambiguously identified yet (Arnould et al. 2007).

Two possible astrophysical sites of r-process production are discussed: supernovae and neutron-star mergers. In the case of supernovae explosions a variety of scenarios for r-element creation by primary and secondary processes were proposed. Neutron-rich jets in rare, magnetohydrodynamic explosions of rapidly rotating stars (e.g. Winteler et al. 2012) and neutron production by neutrino reactions in the helium layer of compact, metal-poor exploding stars (Banerjee et al. 2011) were considered as being potentially responsible for an early enrichment of the young Galaxy with r-process matter. However, supernovae could be a major or even dominant source of r-process elements only if the so-called neutron-driven wind, a low-mass baryonic outflow from newly formed neutron stars (e.g. Woosley et al. 1994; Qian & Woosley 1996; Hoffman et al. 1997), were able to provide an r-process viable environment (Argast et al. 2004). Self-consistent models, however, do not only yield wind entropies that are too low to enable a strong r-process that could make lanthanides and actinides (e.g. Takahashi et al. 1994; Witt et al. 1994; Roberts et al. 2010), but state-of-the-art supernova models with high-fidelity neutrino transport also yield proton-rich conditions instead of neutron excess in the wind ejecta (Hudepohl et al. 2010; Fischer et al. 2010; Janka 2012; Mazzetti et al. 2016).

Recently, growing attention has been paid to mergers of binary neutron stars (NS-NS) and neutron-star black hole (NS-BH) systems as possible r-process sites (Lattimer & Schramm 1976; Lattimer et al. 1977; Eichler et al. 1989), following the confirmation by hydrodynamic simulations that non-negligible amounts of matter, typically about 10^{-3} to several 10^{-2}M_\odot, can be ejected (e.g. Rosswog et al. 1999; Freiburghaus et al. 1999; Arnaud et al. 2007; Metzger et al. 2010; Roberts et al. 2011; Goriely et al. 2011; Korobkin et al. 2012; Bauswein et al. 2013; Goriely et al. 2013; Wanajo et al. 2014; Perego et al. 2014; Just et al. 2015; Sekiguchi et al. 2015; Radice et al. 2016). In contrast to the supernova case, investigations with growing sophistication have so far supported NS merger ejecta as viable sites for strong r-processing (e.g. Wanajo et al. 2014; Sekiguchi et al. 2015; Goriely et al. 2015; Roberts et al. 2016) for steps towards including neutrino effects. In particular, comprehensive nucleosynthesis calculations (Just et al. 2015; Martin et al. 2015) show that the combined contributions from both the dynamical (prompt) ejecta expelled during NS-NS or NS-BH mergers, and the neutrino and viscously driven outflows generated during the post-merger remnant evolution of relic NSs or BH-torus systems can lead to the production of r-process elements from A \gtrsim 90 up to thorium and uranium with an abundance distribution that reproduces extremely well the solar distribution, as well as the elemental distribution observed in low-metallicity stars (Roederer 2011; Roederer et al. 2012).

Despite a roughly 1000 times lower NS merger rate compared to the core-collapse supernova rate, NS-NS/BH mergers could still explain the total amount of r-material in the Galaxy because the amount of ejected r-process-rich matter per NS merger is roughly 1000 times higher than the potential contribution from the neutrino-driven wind of a supernova. Based on observed binary pulsars and population synthesis calculations, the NS-NS merger rate is currently estimated to be within the plausible range of 3 to 190 Myr^{-1} (e.g. Kim et al. 2010; Dominik et al. 2012; Vangioni et al. 2015). Initially there were concerns that the low rate of compact star mergers (with their correspondingly larger ejecta masses per event) in addition to the long time delay of binary mergers after the preceding, iron-producing supernovae would be incompatible with the Galactic enrichment history as deduced from observations of (ultra-)metal-poor stars (Argast et al. 2004). However, more recent models of the chemical evolution of the Milky Way show a much more promising situation. Taking into account a short-lived binary component (with inspiral times of less than 100 Myr), incomplete Galactic mixing and/or the sub-halo merger history of the Milky Way, these new studies conclude that double compact star mergers might indeed be the major producers of r-process elements and might even be responsible for the enrichment of metal-poor stars (Matteucci et al. 2014; Komiya et al. 2014; Mennekens & Vanbeveren 2014; Sien et al. 2014; van de Voort et al. 2014; Vangioni et al. 2015; Wehmeyer et al. 2015; Ishimaru et al. 2015). Although these investigations, which are based on largely different modelling approaches, ranging from traditional, highly simplified box models to hydrodynamical simulations, do not agree in all quantitative details of the picture, the majority of them suggests that compact binary mergers as r-process sites are better compatible with the considerable event-to-event scatter of the r-process abundances in metal-poor stars.

If NS-NS/BH mergers are indeed the main cosmic sources of heavy r-process matter, the rarity of such events would leave little hope for discovering on Earth larger amounts of radioisotopes of cosmic origin like 244Pu. In fact, a recent measurement found a very low 244Pu abundance in deep-ocean reservoirs, about two orders of magnitude lower than expected from continuous production by frequent sources like supernovae (Wallner et al. 2015). In combination with abundance measurements for the Early Solar System this experimental result was therefore interpreted as strong evidence for the origin of 244Pu from compact binary mergers (Hotokezaka et al. 2015).

However, more experimental and observational confirmation with better statistics and based on alternative reservoirs is highly desirable to consolidate the picture suggested
by the existing measurements, which are subject to considerable uncertainties associated with limited statistics and our incomplete knowledge of the probability with which supernova-made nuclei make their way to Earth and finally end up in the investigated sample material. Such caveats certainly justify ongoing efforts to directly identify supernovae as cosmic sources of r-process matter or, alternatively, to derive increasingly stronger bounds to the supernova origin of this matter by searching for r-nuclei in the envelopes of supernova companion stars and for radioisotopes in dated terrestrial sediments. It should be kept in mind that without any unambiguous identification of an r-process source by the in-situ detection of r-nuclei or our understanding of the astrophysical origin of this nucleosynthetic component is based on complex indirect arguments and on theoretical models with their natural limitations. Such limitations are associated with numerous simplifications that still enter the modeling of supernovae as well as compact binary mergers, with constraints set by the finite numerical resolution and by the omission of physics that could play a role like, for example, acoustic waves due to NS vibration (Qian & Woosley 1996); Roberts et al. (2010), fallback in supernovae and associated re-ejection of matter (Fryer et al. 2006), strong neutron-star magnetic fields (e.g. Thompson 2003; Suzuki & Nagataki 2005; Metzger et al. 2007; Vlasov et al. 2014), a rigorous treatment of neutrino oscillations, or non-standard weak-interaction physics.

With the goal to assist future experimental searches we provide here state-of-the-art estimates of the possible production of the actinides. In order to circumvent the uncertainties of current core-collapse supernova and neutrino-wind models, we adopt an optimistic point of view here and assume that the r-process taking place in type-II supernovae is capable of producing elements up to the heaviest actinides and in addition that each such event leads to an r-abundance distribution similar to the one found in the solar system. The striking similarity between the solar distribution of r-element abundances in the 56 \leq Z \leq 76 range and the corresponding abundance pattern observed in ultra-metal-poor stars like CS 22892-052 (Sneden et al. 2003, 2008, 2009) led to the conclusion that every astrophysical event producing r-elements gives rise to a solar system-like r-abundance distribution, at least for elements above Ba. Such observations therefore tend to lend support to our assumption, although recent observations also indicate that star-to-star variations in the r-process content of metal-poor globular clusters may be a common, although not ubiquitous, phenomenon (Honda et al. 2007; Roederer et al. 2010; Roederer 2011).

Section 2 describes the analytical \( \nu \)-driven wind model considered in the present work, while our fitting procedure used to construct an optimal reproduction of the solar system r-abundance distribution is outlined in Sect. 3. The different nuclear inputs used in the present study are detailed in Sect. 4. Finally, our fit to the solar system r-abundances, the astrophysical ranges required for this fit as well as our predictions concerning the actinide production are presented in Sect. 5. Conclusions are drawn in Sect. 6.

2 THE WIND MODEL

Several wind models of analytical or semi-analytical nature exist. They differ in their level of physical sophistication and way to parametrize the wind characteristics. In all cases, the wind is assumed to be spherically symmetric, which appears to be a reasonable first approximation even in two-dimensional simulations, at least at late enough times after core bounce (Pruet et al. 2005; Arcones & Janka 2011). In addition, the wind is generally treated as a stationary flow, meaning no explicit time dependence of any physical quantity at a given radial position \( r \), so that \( \partial x/\partial t = 0 \), let \( x \) be the velocity, temperature, density, internal energy, pressure, entropy, or composition. The validity of this approximation is discussed in Thompson et al. (2001), where it is concluded that stationarity may be reasonably assured, even if some caution is warranted. Newtonian, post-Newtonian, and relativistic descriptions of spherically symmetric, stationary neutrino-driven winds originating from the surface of proto-neutron stars (PNS) have been developed along the lines of a long experience with previous mathematical treatments of the solar wind and of accretion flows onto black holes.

The wind model adopted here corresponds to the analytical Newtonian, adiabatic and steady-state wind model, referred to in the following as NASS, derived by Takahashi & Janka (1997). It provides a simple, fully analytical description of the dynamics of the wind outflow at relatively late times or sufficiently far away from the PNS surface. The NASS wind model relies on the general assumptions listed above, in particular those of a Newtonian PNS gravitational potential and of an adiabatic expansion. In addition, all the elementary \( \nu/\bar{\nu} \) and \( e^-/e^+ \) weak interaction processes are assumed to be frozen out, nuclear \( \beta \)-decays not to affect \( Y_e \) or \( s \), and possible deviations from nuclear equilibrium with regard to strong and electromagnetic interactions to have no influence on the thermodynamical properties of the wind. Under such simplifying assumptions, the NASS model cannot predict any time variations of the entropy \( s \), electron fraction \( Y_e \), or of the wind mass loss rate \( dM/dt \equiv \dot{M} \), which are thus treated as constant input parameters.

The basic NASS wind dynamics in the regime under consideration, and in particular for high enough entropies, is well approximated (Takahashi & Janka 1997; Arnould et al. 2007) by

\[
\frac{1}{2} \nu^2 - \frac{GM_e}{r} + N_A kT \bar{s}_{\text{rad}} = E, \tag{1}
\]

where \( M_e \) is the PNS mass, \( r \) the radius, \( \nu \) the velocity, \( T \) the temperature. The total energy per unit mass \( E \) may be obtained by setting a boundary condition and is usually expressed as a function of the wind energy: \( E = f_w E_{\text{wind}} \), where \( E_{\text{wind}} = 3\nu^2/2 \) and \( v_0 \) equals the local adiabatic sound speed (Arnould et al. 2007). For \( f_w = 1 \), the solutions correspond to a sonic wind, whereas for \( f_w > 1 \) they are of subsonic wind type and usually referred to as breeze solutions. More details about the wind model can be found in Arnould et al. (2007).

The entropy is dominated by photons, electrons and positrons in the wind so that the so-called ‘radiation entropy’ \( s_{\text{rad}} = s_e + s_\gamma + s_{\bar{\nu}} \) is given by

\[
s_{\text{rad}} = s_{\text{rad}}^0 \left( \frac{4}{11} + \frac{7}{11} f_w \right) \quad \text{with} \quad s_{\text{rad}}^0 = \frac{11\pi^2}{45\nu N_A} \left( \frac{kT}{hc} \right)^3, \tag{2}
\]
where \( f_o \) = 1 in the high-T limit when electrons and positrons are highly relativistic, and decreases with \( T \) for high \( s_{\text{rad}} \)-values. In the present study, it is approximated by \( f_o = T_o^2 / (T_o^2 + 5.04) \), where \( T_o \) is the temperature expressed in \( 10^9 \text{K} \) (Witti et al. 1994). Since the nucleosynthesis in the wind is followed by starting at a temperature of \( T_o = 9 \), the total entropy is essentially equal to the radiation entropy (within a few percents). Note that the ‘radiation entropy’ is measured here per baryon in units of the Boltzmann constant \( k_B \) and includes both the photon and lepton contributions, but not the baryonic ones. For the initial conditions adopted here, the latter amounts to typically 9 \( k_B \)/baryon.

In the wind model of Takahashi & Janka (1997), the radial evolution of the velocity, \( v(r) \), and density, \( \rho(r) \), for specified total energy (\( E \)) per unit mass of outflow material (or, equivalent, for given \( f_w \)), given entropy and given mass-loss rate \( M = dM/dt \) is determined by the energy equation (based on Bernoulli’s equation, see Eq. 1) and the continuity equation \( M = 4\pi r^2 \rho(r)v(r) \). The temperature then follows from the assumption of constant entropy, which couples temperature and density. Varying \( f_w \) (or \( E \)), \( s_{\text{rad}} \) or \( M \) therefore also implies different values of the expansion time scale. Within the NASS wind model, the velocity at small radii (and high temperatures) is found to vary as \( v \propto M s_{\text{rad}}^{1/3} \) and consequently significantly increases with the radiative entropy for given \( M \) and \( f_w \).

The NASS equations describe the outflow dynamics (wind and breeze solutions) as functions of radius and as determined by \( M \), \( E \) (or, equivalent, \( f_w \)), and \( s_{\text{rad}} \). These parameters as well as the electron fraction, \( Y_e \), are considered to be independent of each other, which implies that the NASS model does not invoke any physical mechanism by which these characteristic parameters of the flow are coupled. In reality, the physical processes that drive the mass outflow from the PNS surface will determine the values of these quantities and may lead to relations between them.

The NASS model therefore provides a more general description of outflows from new-born NSs (e.g., the usual neutrino-driven wind models mentioned above, where neutrino heating near the PNS surface sets the conditions in the ejecta). This more general modeling approach is an advantage and requirement of our study, which intends to explore also the uncertainty limits of predictions of actinide nucleosynthesis associated with still unsettled aspects of the wind physics (like, e.g., the impact of acoustic waves from NS vibrations or strong magnetic fields). Because of this freedom of the NASS model, however, we have to define suitable ranges of the parameters of the model, which allow us to scan the range of possibilities. Naturally, this can happen only by the investigation of a limited number of cases, which we define as “Ranges I–IV”.

The four ranges of outflow conditions considered in the present study are defined as follows, aiming at a good reproduction of the solar r-process abundances from the first to the third abundance peak. In Range I, we include 150 trajectories with entropies 50 \( \leq s_{\text{rad}} \leq 300 \) in steps of 50, electron fractions 0.30 \( \leq Y_e \leq 0.48 \) in steps of 0.02, mass outflow rates \( M = 0.03, 0.06, 0.30 \times 10^{-5} M_\odot/s \), and \( f_w = 3 \). In Range II, a set of breeze solutions is considered, i.e. entropies 50 \( \leq s_{\text{rad}} \leq 200 \) in steps of 50, electron fractions 0.30 \( \leq Y_e \leq 0.48 \) in steps of 0.02, a single outflow rate of \( M = 0.06 \times 10^{-5} M_\odot/s \), and \( f_w = 3 \). This restricted set of 40 trajectories will be shown in Sect. 3 to still allow for a good fit to the solar system r-abundances and will consequently be used for a relatively detailed sensitivity analysis concerning nuclear uncertainties.

In Range III, wind solutions are considered, i.e. \( f_w \) = 1, with entropies 50 \( \leq s_{\text{rad}} \leq 250 \) in steps of 50, electron fractions 0.30 \( \leq Y_e \leq 0.48 \) in steps of 0.02, and an outflow rate \( M = 0.06 \times 10^{-5} M_\odot/s \).

The astrophysical conditions thus considered are associated with a wide range of expansion time scales \( \tau_{\text{exp}} \). If we define \( \tau_{\text{exp}} \) as the time required for the temperature to drop from \( T_0 = 9 \) to \( T_0 = 2 \), \( \tau_{\text{exp}} \) ranges between 120 and 950 ms for an entropy of \( s_{\text{rad}} = 100 \) and between 18 and 30 ms for \( s_{\text{rad}} = 250 \) at conditions of Range I. In Range II (III), \( \tau_{\text{exp}} = 38 (31) \) ms for the largest entropies of \( s_{\text{rad}} = 200 \), but increases up to 7.3 (7.2) s for \( s_{\text{rad}} = 50 \).

In contrast to the usual behavior of neutrino-driven winds, where higher entropies are associated with increasing expansion time scales (Qian & Woosley 1996), the conditions defined by Ranges I–III exhibit inverse relations, namely greater entropies for shorter expansion time scales. This appeals to some unknown mechanism that can provide such conditions (which is not implausible in view of the fact that ordinary neutrino-driven winds are not found to produce heavy r-process material). The standard behavior of neutrino-driven winds can be reproduced by our NASS model by making use of the relation \( v \propto M s_{\text{rad}}^{1/3} \) and by modifying the outflow rate such that the effect of higher entropies on the wind velocity is compensated. In order to study a case more compatible with neutrino-driven winds and breezes, we therefore consider an additional set of breeze solutions, Range IV, with the following entropies \( s_{\text{rad}} \) and outflow rates \( M \) in \( 10^{-5} M_\odot/s \): (100, 0.6), (125, 0.17), (150, 0.06), (175, 0.015), and (200, 0.006). With \( f_w = 3 \), the corresponding expansion time scales \( \tau_{\text{exp}} \) of these five events are 72, 86, 106, 209, and 296 ms, respectively, which clearly increase for increasing entropies. For each of these combinations of entropy and outflow rate, 15 events for electron fractions varying within 0.20 \( \leq Y_e \leq 0.48 \) in steps of 0.02 are considered. Range IV therefore includes 75 events in total.

3 FITTING THE SOLAR SYSTEM R-ABUNDANCE DISTRIBUTION

In a similar way to that developed in the multi-event canonical s- or r-process models (Goriely & Arnould 1996) (Goriely 1997), it is possible to define a superposition of a large number of \( \nu \)-driven wind components (“events”) that correspond to different thermodynamic conditions. Each event is characterized by a given entropy \( s_{\text{rad}} \), electron fraction \( Y_e \), outflow rate \( M \), and wind energy scaling factor \( f_w \).

The combination of r-process events that provides the best fit to the solar abundances can then be derived with the aid of an iterative inversion procedure that has been applied to astronomical inverse problems (Lucy 1974) but also to parametric r-process calculations (Bouquell et al. 1996) (Goriely & Arnould 1996) (Goriely 1997). The solar abundance \( N_{Z,A}^{\odot} \) of a nuclide \((Z,A)\) is approximated by the weighted superposition of the abundances \( n(Z,A; s_{\text{rad}}, Y_e, M, f_w) \) resulting from all astrophys-
rical events according to
\[ N^{(0)}_{Z,A} \simeq \sum_{s_{\text{rad}}, Y_e, \dot{M}, f_w} n(Z, A; s_{\text{rad}}, Y_e, \dot{M}, f_w) \Phi(s_{\text{rad}}, Y_e, \dot{M}, f_w), \]
where \( \Phi(s_{\text{rad}}, Y_e, \dot{M}, f_w) \) represents the statistical weight of the event \((s_{\text{rad}}, Y_e, M, f_w)\). The recursion relation
\[ \Phi^{(r+1)}(s_{\text{rad}}, Y_e, \dot{M}, f_w) = \Phi^{(r)}(s_{\text{rad}}, Y_e, \dot{M}, f_w) \sum_{Z,A} N^{(0)}_{Z,A} \times n(Z, A; s_{\text{rad}}, Y_e, \dot{M}, f_w) \]
is used in order to obtain an “improved” \((r + 1)\)th estimate of \( \Phi(s_{\text{rad}}, Y_e, \dot{M}, f_w) \) from the rth iteration \( \Phi^{(r)} \). \( N^{(r)}_{Z,A} \) is defined by
\[ N^{(r)}_{Z,A} = \sum_{s_{\text{rad}}, Y_e, \dot{M}, f_w} n(Z, A; s_{\text{rad}}, Y_e, \dot{M}, f_w) \times \Phi^{(r)}(s_{\text{rad}}, Y_e, \dot{M}, f_w). \]

The iteration procedure starts with a uniform distribution of initial weights \( \Phi^{(0)}(s_{\text{rad}}, Y_e, \dot{M}, f_w) \) (i.e. all events have initially the same weight) and converges after several iterations to a “best-fit” abundance curve \( N_{Z,A} \). The corresponding weight profile \( \Phi(s_{\text{rad}}, Y_e, \dot{M}, f_w) \) allows us to identify the events that contribute most significantly to the synthesis of each fitted element.

Two different sets of solar system r-abundance distributions are considered in the present study. They differ by the way the s-process contribution to the solar system is estimated. Goriely (1999) used the multi-event canonical s-process model and included a detailed analysis of observational, astrophysical and nuclear physics uncertainties, while Bisterzo et al. (2014) estimated the s-process abundances on the basis of a Galactic chemical evolution model with AGB yields based on parametrized \(^{13}\)C profiles to generate the s-process irradiation. Due to the more complex approach, uncertainties are not estimated in the latter case and the contribution from the weak s-component in massive stars is inherently accounted for by our parametric wind model.

4 NUCLEAR PHYSICS INPUT

The nucleosynthesis is followed with a reaction network including all 5000 species from protons up to \( Z = 110 \) lying between the valley of \( \beta \)-stability and the neutron-drip line. All charged-particle fusion reactions on light and medium-mass elements that play a role when the nuclear statistical equilibrium freezes out are included in addition to radiative neutron captures and photodisintegrations. The reaction rates on light species are taken from the NETGEN library, which includes all the latest compilations of experimentally determined reaction rates (Xu et al. 2013). By default, experimentally unknown reactions are estimated with the TALYS code (Goriely et al. 2008; Koning et al. 2012) on the basis of the HFB-21 nuclear masses (Goriely et al. 2010), the HFB plus combinatorial nuclear level densities (Goriely et al. 2008b) and the QRPA E1 strength functions (Goriely et al. 2004).

| FRDM        | Reactions rates determined with the 2012 version of the FRDM mass model (Möller et al. 2016); all other inputs remaining identical; |
|-------------|---------------------------------------------------------------------------------------------------------------------------------|
| HFB-31      | Reactions rates determined on the basis of the Hartree-Fock-Bogoliubov (HFB) HFB-31 mass model (Goriely et al. 2016); all other inputs remaining identical; |
| DIM         | Reactions rates determined on the basis of the DIM Gogny-HFB mass model (Goriely et al. 2009); all other inputs remaining identical; |
| FRDM        | Reactions rates determined with the 2012 version of the FRDM mass model (Möller et al. 2016), the backshifted Fermi Gas model for nuclear level densities (Koning et al. 2008) and Lorentzian-type E1 strength function (Kopecky & Uhl 1999); \( \beta \)-decay rates are taken from the Random Phase Approximation and FRDM-based Q-values (Möller et al. 2003); Fission probabilities are based on the Myers & Swiatecki (1999) fission barriers and the fragment yields on the GEF model (Schmidt & Jurado 2012). |

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nuclear physics set essentially includes so-called phenomenological macroscopic approaches in contrast to the microscopic input characterizing the standard set:

- FTS: reaction and β-decay rates are identical to the default models, but fission probabilities are based on the Myers & Swiatecki (1999) fission barriers and the fragment yields on the GEF model (Schmidt & Jurado 2012);
- BETA: β-decay rates from the Gross Theory are replaced by the Tamm-Dancoff approximation (Klapdor et al. 1984); all other inputs remaining identical to the standard set.

5 RESULTS

5.1 Actinide production

The solar system abundances have been fitted assuming different ranges of astrophysical conditions for the ν-driven wind and different nuclear physics inputs, as described in the previous sections. One example (Case 1; Table 1) of a fit corresponding to the Range I of astrophysical conditions and the standard nuclear physics input, is shown in Fig. 2. It can be seen that the solar distribution (in this case, taken from Goriely 1999) is rather well fitted, although deviations can be observed, in particular in the rare-earth region. The corresponding distributions of entropies and electron fractions are illustrated for this standard case in Fig. 3. For illustration, additional fits with Range II of astrophysical conditions and the nuclear physics inputs corresponding to DIM and FRDM (Cases 7 and 11, respectively; Table 1) are given in Fig. 3. It will also be noticed that the restricted Range II is already sufficient to provide the conditions needed to reproduce the solar system distribution fairly well. The statistical weights of entropies and electron fractions needed to obtain these fits are obviously dependent on the adopted range of astrophysical conditions as well as the nuclear physics inputs, as shown in Fig. 4.

Considering different combinations for the solar r-abundance distributions, ranges of thermodynamic conditions and nuclear physics inputs, quite some different predictions for the production of actinides can be derived as summarized in Table 1. In particular, it can be seen that wind solutions (fw = 1) in the Range III of thermodynamic conditions lead to a significantly lower production of some actinides compared to the breeze solutions (fw = 3 in Range II). The specific conditions defined in Range IV lead to an actinide production quite similar to the one obtained in Range II.

Nuclear physics inputs, in particular nuclear mass models (and the corresponding rates) as well as β-decay rates, have also a non-negligible impact on the abundance predictions, as already well established for decades. Uncorrelated lower and upper limits to the production of the long-lived actinides can be deduced and are also given in Table 1. The uncertainties for the 232Th production are found to be considerably larger than those for the production of 244Pu and 247Cm. For comparison, the upper and lower limits estimated within the multi-event canonical model (Goriely & Arnould 2001) on the basis on very different astrophysical conditions and nuclear physics inputs are also given in Table 1.

For completeness, Table 1 also gives the estimated age of the ultra-metal-poor star CS 31082-001. Indeed, accurate observations of heavy r-elements have been used to estimate the age of ultra-metal-poor stars on the basis of the fundamental assumption that the r-process is universal (Sneden et al. 1996; Cowan et al. 1997; Goriely & Clerbaux 1999). In particular, if Th and U lines could be observed accurately and simultaneously in metal-poor stars, a relatively reliable age estimate could be derived from the expression

\[ \log \left( \frac{\text{Th}}{U} \right)_{\text{obs}} = \log \left( \frac{\text{Th}}{U} \right)_{\text{r}} + \log e \left( \frac{1}{\tau(\text{Th})} - \frac{1}{\tau(U)} \right) T_{\text{T},\text{Th}} \]

(6)

where \( \tau(U) = 6.45 \text{ Gyr} \) is the characteristic α-decay timescale of 238U and similarly \( \tau(\text{Th}) = 20.27 \text{ Gyr} \) for 232Th. Note that the Th abundance in the r-process ratio of Eq. (6)
Table 2. Upper and lower limits of the yields (in $M_\odot$) of Pb and long-lived actinides ejected per supernova assuming the matter accumulated in the $\nu$-driven wind corresponds to $7 \times 10^{-4} M_\odot$ (Takahashi et al. 1994).

| Nuc  | Min    | Max    |
|------|--------|--------|
| Pb   | 5.26E-07 | 2.19E-06 |
| $^{232}$Th | 5.42E-09 | 5.54E-07 |
| $^{235}$U | 1.77E-08 | 5.25E-07 |
| $^{236}$U | 1.64E-08 | 5.01E-07 |
| $^{238}$U | 1.74E-08 | 5.88E-07 |
| $^{237}$Np | 3.42E-08 | 6.38E-07 |
| $^{244}$Pu | 2.37E-08 | 2.75E-07 |
| $^{247}$Cm | 2.19E-08 | 1.39E-07 |

6 CONCLUSIONS

We derived updated estimates of the production of the radioactive actinides of $^{232}$Th, $^{235,236,238}$U, $^{237}$Np, $^{244}$Pu, and $^{247}$Cm and of the corresponding uncertainty ranges based on the assumption that the neutrino-driven wind of the protoneutron star in core collapse supernovae is able to provide r-process viable conditions and can well reproduce the universal r-process abundance pattern observed in the Sun and found in metal-poor stars. Since current state-of-the-art hydrodynamical models of supernova explosions and of the neutrino-driven wind do not yield the dynamic and thermodynamic conditions needed for the production of heavy r-process material, we base our study on the simple, analytical NASS (Newtonian, adiabatic, steady-state) wind model and take into account the mass-weighted superposition of a large number of wind components with different nucleosynthesis.

5.2 Actinide yields per supernova event

Table 2 gives the abundances of Pb and of the main actinides (in the Si=10$^6$ scale) produced by the r-process in the $\nu$-driven wind, assuming the r-process is universal and produces an abundance distribution identical to the solar one. To estimate the yields of ejected material per supernova event, we have to know the total amount of matter accumulated in the $\nu$-driven wind and able to make r-process elements. Since no realistic $\nu$-driven wind model exists that leads to a successful r-process, this quantity remains unknown. For this reason, we adopt here a fiducial value of $M_{\text{wind}} = 7 \times 10^{-4} M_\odot$ ejected per Galactic supernova as well as an amount of the r-only nucleus $^{130}$Te produced by each supernova of about $6 \times 10^{-6} M_\odot$ (Takahashi et al. 1994). Using now an abundance of 1.59 of $^{130}$Te in the Si=10$^6$ scale (Figs. 1, 2, 4), it is straightforward to estimate the ejected yields for each actinide. The upper and lower limits of these yields are given in Table 2 on the basis of the minimum and maximum abundances given in Table 1. Clearly, a large uncertainty factor should also be applied to the $M_{\text{wind}}$ value and correspondingly to the yields, or equivalently the yields of Table 2 should be taken proportional to the $M_{\odot}/(7 \times 10^{-4} M_\odot)$ where $M_{\odot}$ is the still unknown total mass of wind ejecta per supernova that contribute to the r-process production. A rather firm theoretical upper limit for this number may be a few $10^{-3} M_\odot$ (close to the maximum total mass of neutrino-driven wind ejecta; R. Bollig, private communication), but according to present state-of-the-art supernova models $M_{\odot}$ is expected to vanish (Hüdepohl et al. 2010, Fischer et al. 2010, Janka 2012, Mirizzi et al. 2016). It should also be recalled here that our numbers in Table 2 rely on the fundamental assumption that the r-process taking place in core-collapse supernovae is capable of producing elements up to the heaviest actinides and, in addition, that each of such events leads to an r-abundance distribution similar to the one found in the solar system.

corresponds to the $^{232}$Th value after decay of its shorter-lived progenitors $^{236}$U and $^{244}$Pu, and the U abundance corresponds to the $^{238}$U contribution only. Th and U lines have been observed in particular in the CS 31082-001 star with a log(U/Th) = $-0.94 \pm 0.09$ (Chyrel et al. 2001 and private communication). The 0.09 dex observational error gives rise to a $\pm 2$ Gyr uncertainty on the estimate of $t_\nu$, Th. For each simulation, the estimated age of CS 31082-001 is given in Table 1. The ages obtained are reasonably consistent with the WMAP estimate of 13.8 Gyr (Ade et al. 2015).

5.2 Actinide yields per supernova event

Figure 4. (Color online). Same as Fig. 2 but for events with Range II conditions and the nuclear physics inputs corresponding to D1M and FRDM.

Figure 5. (Color online). Same as Fig. 3 but for the statistical weights corresponding to the abundance fit shown in Fig. 4 with D1M mass model and Range II conditions.
relevant characteristics of entropy, expansion time scale, and neutron excess. The set of chosen conditions is constrained by the ability of the integrated wind material to match the solar r-abundance distribution. In order to explore the sensitivity of our estimates for the actinide production to uncertain nuclear physics, we tested the influence of six different sets of nuclear-rate ingredients.

The consideration of neutrino-driven winds of supernovae as possible r-process site, despite the unfavorable conditions provided by current hydrodynamical models, and the combination of wind components under the mentioned constraint, can be justified by the fact that also the state-of-the-art models still suffer from major uncertainties, e.g. with respect to neutrino opacities in correlated nuclear matter, the effects of potentially strong magnetic fields inside and around the nascent NS, or the incomplete exploration of neutrino-oscillation effects and possible non-standard weak interaction physics in the PNS environment. On the other hand, despite considerable modeling progress and generally more promising properties of the ejecta dynamics, also NS-NS and/or NS-BH mergers are by far not established as the main sources of heavy r-process nuclei, because in this case too, major uncertainties still affect the weak-interaction sector as well as the description of strong magnetic field effects.

Further observational efforts for a positive confirmation of the one or the other or of both possible sources are therefore needed. This includes searches of electromagnetic transients associated with the radiation emission of NS-NS/BH merger ejecta heated by the radioactive decay of r-process nuclei (see for example, Metzger et al. 2010; Roberts et al. 2011; Goriely et al. 2011; Korobkin et al. 2012; Bauswein et al. 2013; Kasen et al. 2015; Martin et al. 2015) as well as the exploration of cosmic and terrestrial reservoirs for signatures of freshly produced r-nuclei. Our work is intended to facilitate the observational and experimental analyses of the latter kind and their interpretation.

We find a considerable spread of the results of actinide yields with the largest uncertainty (a factor of ~100) for $^{232}$Th and the lowest uncertainty for $^{244}$Pu (factor of ~12) and for $^{247}$Cm (factor of ~7), with supernovae expanding wind solutions producing considerably less actinide material than more slowly, subsonically expanding breeze outflows. For investigations of terrestrial material like recently performed by Wallner et al. (2015), it is interesting to know the isootope-production ratio of $^{244}$Pu compared to the long-lived radio-active nucleus $^{60}$Fe. Current supernova models predict a yield of $^{60}$Fe of $\sim 3 \times 10^{-3}$ $M_\odot$ per massive-star death or $\sim 4 \times 10^{-5}$ $M_\odot$ per supernova (Sukhbold et al. 2015). Since this theoretical value seems to exceed estimates based on cosmic-rays near the Earth by about a factor of 2 (Sukhbold et al. 2015), we consider here a $^{60}$Fe output per exploding massive star of $\sim 2 \times 10^{-5}$ $M_\odot$. With this number we obtain a theoretical range for the supernova-produced $^{244}$Pu/$^{60}$Fe isotope ratio between roughly $1.2 \times 10^{-3}$ and $1.4 \times 10^{-2}$, using the yields of Table 2. With experimentally determined limits of less than $10^{-4}$ for their crust and sediment samples, Wallner et al. (2015) set a bound still more than a factor of 10 below our lower limit. Therefore this bound seems to
exclude a recent insemination of the Earth by r-process material from a frequent source like supernovae, in particular from a nearby supernova ∼2.2 My in the past. However, the exclusion may not be as convincing as suggested by the two orders of magnitude discrepancy advocated by Wallner et al. (2015). Not only the probability with which $^{244}$Pu from a possible supernova origin ends up in the investigated material samples is uncertain, also the extreme sensitivity of the actinide production to the model variations tested in our work should be taken as a warning.

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