r-Process Abundance Universality and Actinide Cosmochronology

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Abstract

We review recent observational and theoretical results concerning the presence of actinide nuclei on the surfaces of old halo stars and their use as an age determinant. We present model calculations which show that the observed universality of abundances for $56 < Z < 75$ elements in these stars does not necessarily imply a unique astrophysical site for the \textit{r}-process. Neither does it imply a universality of abundances of nuclei outside of this range. In particular, we show that a variety of astrophysical \textit{r}-process models can be constructed which reproduce the same observed universal \textit{r}-process curve for $56 < Z < 75$ nuclei, yet have vastly different abundances for $Z \geq 75$ and possibly $Z < 56$ as well. This introduces an uncertainty into the use of the Th/Eu chronometer as a means to estimate the ages of the metal deficient stars. We do find, however, that the U/Th ratio is a robust chronometer. This is because the initial production ratio of U to Th is almost independent of the astrophysical nucleosynthesis environment. The largest remaining uncertainties in the U/Th initial production ratio are due to the input nuclear physics models.

Key words: Stars: abundances, supernovae: general

1 Introduction

Rapid neutron-capture (the \textit{r}-process) is responsible for producing about half of the elements heavier than iron. It is believed to occur in an explosive stellar environment in which the neutron capture time scale is much shorter than typical beta-decay lifetimes near the line of stable nuclei. The nuclear reaction flow can then proceed through extremely neutron-rich unstable nuclei. The fact that the heavy radioactive actinide nuclei, U and Th, are generated in the \textit{r}-process is of particular interest. These nuclides have half lives
$[t_{1/2}^{(238}\text{U}) = 4.47 \times 10^9 \text{ y}, t_{1/2}^{(232}\text{Th}) = 1.40 \times 10^{10} \text{ y}]$ which are comparable to the cosmic age. These chronometers have taken on renewed recent attention as their absorption lines have been identified (e.g. Sneden et al., 2002; Cayrel et al., 2001; Honda et al., 2003a,b) in metal deficient stars.

The inferred abundances of Th and/or U can be used to estimate stellar ages. Metal deficient stars are believed to be the oldest stars in the Galaxy, and their surface abundances have probably not changed (except for radioactive decay) since these stars were formed. Moreover, their age can be regarded as the Galactic age and a lower limit to the cosmic age. As a chronometer, this method is particularly appealing since it avoids the usual Galactic chemical evolution model dependence (Meyer & Schramm, 1986) associated with Solar-System radio cosmochronometry. The Th or U on the surface of an old low-metallicity halo star were probably generated in a single nucleosynthesis event. Hence, the surface abundance of radioactive element $Y_r$ ($r=\text{Th or U}$) is given to a very good approximation by

$$Y_r(\Delta T) = Y_r(0)exp(-\Delta T/\tau_r)$$  \hspace{1cm} (1)

where $\Delta T$ is time since nucleosynthesis and $\tau_r$ is the mean life of the $r$-element, \textit{i.e.} $\tau_r = t_{1/2}/\ln 2$. For each radioactive element, one can solve Eq. (1) to find $\Delta T$. It is best to utilize abundance ratios relative to an element with a nearby absorption feature (e.g. Eu). Therefore, $\Delta T$ is usually given by

$$\Delta T = 46.7(\log(\text{Th/Eu})_0 - \log(\text{Th/Eu})_T) ,$$ \hspace{1cm} (2) \hspace{1cm}$$

$$\Delta T = 21.8(\log(\text{U/Th})_0 - \log(\text{U/Th})_T) ,$$ \hspace{1cm} (3)

in units of Gyr, where the index 0 denotes the initial production ratio, while the index $T$ refers to the presently observed value. (In these equations we denote $Y_{\text{Th}} = \text{Th}, Y_{\text{Eu}} = \text{Eu},$ and $Y_{\text{U}} = \text{U}$.) The only uncertainties are, therefore, those in the determination of the present stellar abundances themselves, and those due to uncertainties in model estimates of the initial production ratios. [That is, as long as the produced actinide nuclei have not passed through stellar CNO burning where they might be destroyed by photo-induced fission (Malaney, Mathews & Dearborn, 1989).]

In view of the significance of this independent measure of the Galactic age, it becomes important to scrutinize and quantify these remaining uncertainties as much as possible. In this paper we are primarily concerned with the astrophysical uncertainties in the initial production abundances. We show that there is indeed considerable uncertainty in using only a single Th or U radiochronometer, even when the universally observed Solar-System $r$-process abundances are well reproduced for lower-mass nuclei. We also establish that
the Th/U chronometer is quite robust and somewhat independent of astro-
physical model uncertainties.

For some time (cf. Truran, 1981; Mathews & Cowan, 1990) r-process elements
in metal deficient stars have been interpreted as evidence for a universal r-
process abundance distribution in operation in the early Galaxy. In particular,
more recent observations (Sneden et al., 2002, 1998, 2000; Johnson & Bolte,
2001) all show similar abundance distributions for \( Z > 56 \) elements. This
feature is often referred to as the “universality” of the r-process. Hence, it is
generally believed that, at least for \( Z > 56 \) elements, the astrophysical site
and associated yields of r-process nucleosynthesis are unique. Based upon this
assumption, Sneden et al. (2002) estimated the ages of several stars using
the ratio of Th/Eu at the time of formation of the Solar System as the initial
production ratio [even though Solar-System material has experienced multiple
supernovae before its formation and has experienced Th decay]. The analyses
of these stars all indicated similar present ages of about 14 Gyr ± 4.

There are, however, some reasons to question the assumption of a universal
r-process abundance curve. The material out of which these metal poor stars
were formed is likely to have experienced only one or two supernovae before
incorporation into the star. Depending upon which particular progenitor su-
pernova was in operation, there might be substantially different abundance
distribution curves for these stars, compared to the ensemble average repre-
sented in Solar-System material (cf. Ishimaru & Wanajo, 1999). Moreover,
quite recently, Cayrel et al. (2001) have reported the observation of peculiar r-
process elements in the metal deficient star CS31082-001. This is the first star
for which a uranium line was also detected. This star has the strange feature,
however, that the ratio of Th to Eu is greater than that of Solar material. This
would imply (on the bases of Th/Eu) that this star is younger than the Sun.
This seems unlikely in view of its low metallicity, \([\text{Fe}/\text{H}] \sim -2.9\). Furthermore,
the Th/Eu age is in contradiction with the U/Th age for this star which is
12 ± 3 Gyr. Further evidence of Th/Eu uncertainty is apparent in the recent
data of Honda (2002) and Honda et al. (2003a,b). They have reported on
r-process element abundance distributions in two other metal-deficient stars.
These stars also show different abundance distribution patterns for \( Z \geq 75 \).

Even the stars studied in Sneden et al.(1996) and Sneden et al.(2000) may show
deviations from a universal r-process distribution for lighter \( Z < 56 \) nuclei. For
example Sneden et al.(2000) noted divergence from the solar r-process for a few
elements in CS22892-052. Cowan et al. (2002) also noted some divergence in
the star BD +17 3248, but those data are somewhat uncertain. This, together
with meteoritic evidence, has been taken as an indication (Qian & Wasserburg,
2000) that two different r-process environments could be in operation. All in
all, the observational data seem to indicate that the universality of r-process
elements may be broken for \( Z \geq 75 \) elements and possibly \( Z \leq 56 \) as well.
In this paper, we wish to clarify the astrophysical model dependence for these stellar r-process chronometers. Several previous investigations (Goriely & Arnold, 2001; Wanajo et al., 2002; Schatz et al., 2002; Qian, 2002; Otsuki et al., 2003) of the uncertainties in actinide chronometers can be found in the literature. The paper by Goriely & Arnold (2001) and Schatz et al. (2002) were primarily directed toward understanding the nuclear uncertainties. For example, Goriely & Arnold (2001) considered 32 different models for r-process actinide production based upon different nuclear physics input for fission barriers, nuclear masses, beta-decay rates, etc. In Schatz et al. (2002), it was found that the Pb abundance was useful to constrain nuclear models. These calculations, however, were made in the context of schematic “canonical event” models which were constrained to reproduce Solar-System r-process abundances. Hence, universality for all elements up to Z=82 was imposed. In another related work, Wanajo et al. (2002) have attempted to clarify the age of CS31082-001 in the context of a specific “neutrino-driven wind” model, but with only electron fraction and the outer boundary temperature as free parameters. Qian (2002) even shows on the basis of the astrophysical observations that the production of the elements with A > 130 is not robust. All of these works have demonstrated some uncertainties in the Th/Eu chronometer, while better results are obtained using the U/Th chronometer.

The present work differs from the previous works in two important ways: 1) Unlike Goriely & Arnold (2001) and Schatz et al. (2002), our focus is on the astrophysical rather than nuclear uncertainties; 2) Rather than to focus on a particular wind model as in Wanajo et al. (2002) and Otsuki et al. (2003), we consider wide range of plausible astrophysical models and parameters all of which reproduce the universality in the abundances for 56 < Z < 75 noted in observations. We also explicitly consider neutrino interaction effects.

From the observations and our theoretical calculations, we conclude that the astrophysical site for r-process nucleosynthesis is probably not unique, even though there is an observed universality of abundances. That is, a variety of astrophysical models can be constructed which reproduce the same apparent universal abundance curve for elements with 56 < Z < 75, but which give large variations in abundances for elements with Z ≥ 75 and/or Z ≤ 56. Hence, it is dangerous to use the Th/Eu chronometer to estimate the age of metal deficient stars. Moreover, the production ratio of the Th/Eu chronometer is strongly dependent upon the nucleosynthesis environment. On the other hand, we demonstrate that the U/Th production ratio is almost independent of the nucleosynthesis environment, confirming that this ratio is robust as a chronometer.

In what follows, we first review in more detail the recent observational results for metal deficient halo stars in section 2. Results of theoretical calculations are shown in section 3. In section 4, we will summarize the viability of the
nuclear cosmochronometers.

2 Observational data

As noted above, it has been shown (Sneden et al., 2002, 1998, 2000) that the star CS22892-052 confirmed the previously noted fact (Spite & Spite, 1978; Truran, 1981; Gilroy et al., 1988) that r-enhanced stars show an abundance distribution which is similar to that of Solar r-process material for Z>56 elements.

Several lighter elements (Z≤56), which would also be generated in the r-process, were also detected in this star. These elements, however, showed a different abundance distribution from that of Solar material. The agreement between the heavier elements (Z>56) and scaled Solar-System abundances has been reported for other metal deficient stars [e.g. HD115444 (Westin et al., 2000), HD126238, HD186478, HD108577 (Johnson & Bolte, 2001)]. In addition, there is also evidence (Sneden et al. 2002; Aoki et al. 2003) that the europium isotope ratios in several r-process enhanced stars are consistent with the Solar r-process isotope ratio. This further enhances the evidence of a single universal abundance curve for Z > 56 elements. Hence, at least for Z>56 elements, it is generally believed that astrophysical site for r-process nucleosynthesis is unique. If one can therefore assume that the Solar-System and metal-deficient stars have the same abundance distribution when they form, then one can use the Solar-System abundances as the initial production ratio. This approach has the problems that the material in the Solar System represents an average of the ejecta from many supernovae, and the Th and U present when the Solar System formed will have decayed from its initial production ratio. Nevertheless, this method is still useful as a means to estimate an upper limit on the age of these stars. Several works have estimated the ages of those metal deficient stars using a scaled Solar Th/Eu value (Sneden et al., 2002, 1998, 2000; Johnson & Bolte, 2001).

However, as noted above, Cayrel et al. (2001) have reported on a uranium line for the star CS31082-001. Although their abundance distribution shows a similar pattern to the Solar System for 56 < Z < 75 elements, there are large differences for Z ≥ 75 elements. In addition to the fact that the Th/Eu abundance ratio is larger than in the Sun, this star has less Pb than in Solar material (Hill et al., 2001).

These two facts are strange because U and Th decay into Pb. As noted above, these facts would indicate that this star is much younger than the Sun in spite of its lower metallicity. Moreover, this age is, however, in conflict with the U/Th age for this star.
Furthermore, Honda (2002) and Honda et al. (2003a,b) have reported on r-process elements in several more metal-deficient stars which were observed using the SUBARU/High Dispersion Spectrometer (HDS). Of particular interest are the stars HD6268 and CS30306-132 (Honda, 2002; Honda et al., 2003a,b). These two stars show a large Th/Eu ratio which is comparable to that of Solar material in spite of their lower metallicity.

In summary, the observations all seem to indicate the following: 1) For $56 < Z < 75$ elements: the r-process abundance distribution appears to obey a universal curve; 2) For $Z \geq 75$ and some $Z < 56$ elements: the r-process abundance distribution may not always coincide with a universal abundance curve.

All of this implies that the r-process nucleosynthesis environment may not be unique even though a universal abundance curve is produced for $56 < Z < 75$. In the next section we seek to explain these trends in the context of models for the r-process.

3 Theoretical calculation

We wish to clarify the dependence of the abundance distribution on the astrophysical environment. Although it is generally believed that the astrophysical site for the r-process is an explosive event, the precise environment has not yet been unambiguously identified. Type II SNe or neutron-star mergers have been proposed as two possible sites (e.g. Mathews & Cowan 1990) with the neutrino-energized wind above the proto-neutron star (Woosley et al., 1994) being the currently most popular paradigm [see however Qian and Woosely (1996), Cardall and Fuller (1997) and Meyer et al. (1998)]. In the following, we base our schematic parameter study on two dynamical models. One is the neutrino-energized wind model (Woosley et al., 1994; Otsuki et al., 2000). The other is an exponential model. We believe that these parameter studies should approximate the gamut of possible r-process models such as might also occur, for example, in neutron-star mergers or prompt supernova explosions.

3.1 Hydrodynamic wind model

For the wind model, we use a spherical steady-state flow approximation for the neutrino-driven wind (cf. Qian & Woosley 1996; Qian 2000; Takahashi & Janka 1997; Otsuki et al. 2000). The hydrodynamic flow is deduced from the following non-relativistic equations:

$$4\pi r^2 \rho v = \dot{M},$$

(4)
\[ \frac{v^2}{2} - \frac{MG}{r} + N_A k T s_{\text{rad}} = E, \quad (5) \]

\[ s_{\text{rad}}(\leq s) \sim s_{\text{rad}}^{(0)} = \frac{11\pi^2}{45 \rho N_A} \left( \frac{kT}{\hbar c} \right)^3, \quad (6) \]

where \( \dot{M} \) is the rate at which matter is ejected by neutrino heating from the surface of the proto-neutron star, and \( k \) is the Boltzmann constant. In equation (5), \( M = 1.4 M_\odot \) is the protoneutron star mass, the total energy \( E \) is fixed by a boundary condition on the asymptotic temperature \( T_b \)

\[ E = N_A s_{\text{rad}} k T_b. \quad (7) \]

For simplicity, in the present work we utilize an adiabatic (constant entropy) wind rather than to compute the neutrino heating explicitly (e.g. as in Otsuki et al., 2000; Wanajo et al., 2001). This is adequate for our purpose which is to sketch the dependence of the abundances on the nucleosynthesis environment. Nevertheless explicit charged and neutral-current neutrino-nucleus interaction effects on abundances are included as described below.

Using this model, we can calculate time profiles of temperature, matter, and the neutrino density for material flowing away from the proto-neutron star. These are then input into a nucleosynthesis network where the neutron density and abundance yields are computed. The coordinate \( r \) was chosen such that when \( T_9 = 9.0, r = 14 \) km. That way all trajectories experience the same initial neutrino luminosity.

### 3.2 Exponential models

There are several theoretical calculations for r-process nucleosynthesis with a longer timescale than that of the wind models, e.g. in prompt supernovae. To model this we have used the following parameterized temperature and density profile.

\[ T_9 = 9.0 \exp(-t/t_{\text{exp}}) + 0.6, \quad (8) \]

\[ \rho = 3.3 \times S/T^3. \quad (9) \]

Here, \( S \) is the entropy and \( t_{\text{exp}} \) is the dynamical timescale.
3.3 Nucleosynthesis

Our nucleosynthesis code is based upon the dynamical network calculation described in Meyer et al. (1992) and Woosley et al. (1994), but with several important modifications. For one, an extensive light-element neutron-rich reaction network has been added as described in Teresawa et al. (2001) and Orito et al. (1997). This light-element network can be important for high-entropy short dynamical timescale environments. We also compute the alpharich freezeout and the $r$-process in a single network rather than to split this calculation into two parts as was done in Woosley et al. (1994). Some results of our calculations for various parameters are shown on Fig. 1. The calculations shown on this figure are for a constant neutrino luminosity of $L_\nu = 10^{51}$ erg sec$^{-1}$. In Fig. 2, we show the dependence on neutrino luminosity. We have included effects of neutrino-nucleus interactions on the nucleosynthesis yields. For more details of this code, see Terasawa et al. (2001) and reference therein.

3.4 Results

A sample of model parameters studied in the present work are summarized in Table 1 and Figures 1-3. As noted below, most of these models reproduce the observed universality of elemental abundances for $56 < Z < 70$. For illustration we also show the implied europium isotope fraction $fr(^{151}Eu) \equiv ^{151}Eu/(^{151}Eu + ^{153}Eu)$. Most of these models are also consistent with the observed isotope fraction of $fr(^{151}Eu) = 0.5 \pm 0.1$ (Sneden et al. 2002; Aoki et al. 2003).

3.4.1 Wind model

Figures 1a-d and 2 illustrate the dependence of the nucleosynthesis yields on various parameters of the wind models. Note, that all of these models are constrained to reproduce the observed universal abundances for $56 < Z < 75$ as shown by the dots on Figure 1a. We have not included the decay back to Pb from long-lived U and Th. Here we only require that the initial production of Pb is less than the observed Pb to account for this decay back. Ultimately, a quantitative account of Pb is important (Schatz et al. 2002) for constraining the nuclear physics input to the $r$-process and will be considered in a subsequent work.

Figure 1a shows the effects of entropy. Changing the entropy essentially alters the neutron-to-seed ratio as the $r$-process begins. Note, that all of these models show an almost identical abundance distribution for $56 < Z < 75$.
elements. Clearly, the observed universality of the r-process is maintained for these elements. On the other hand, elements with $Z \geq 75$ show much different distributions. Obviously, the Th/Eu ratios would be substantially different for models with different entropy, even though the universal abundance distribution for $Z \leq 75$ elements is obtained.

We have also studied effects of altering the electron fraction (Fig. 1d) and the dynamical time scale (Fig. 1c). These parameters similarly affect the neutron-to-seed ratio at the onset of the $r$-process, and produce nearly equivalent results to those shown on Figure 1a, i.e. the abundance distribution for $Z < 75$ elements is unaffected, while elements with $Z \geq 75$ are significantly altered. Note that varying $Y_e$ has the smallest effect on the distribution, and hence, does not by itself give a fair representation of the model uncertainties.

The asymptotic temperature $T_b$ at which neutron captures freeze out also affects the abundance distribution as shown in Figure 1b. In this case, the freeze-out temperature essentially determines the $r$-process path at the termination of the $r$-process. A discussion of this dependence on asymptotic temperature also appears in Terasawa et al. (2002) and Wanajo et al. (2002). Note, that in all three of the models chosen, the abundances between $60 \leq Z \leq 75$ are consistent with the universal curve. In this case, however, both elements with $Z < 60$ and $Z > 75$ are substantially different.

In Figure 2 we also show the dependence upon neutrino luminosity. Neutrino-induced beta-decay can also affect the abundance distribution. The main effect of neutrino luminosity in these models is to provide neutrino-induced neutron emission. For $60 < Z < 70$, this helps to smooth the abundance distribution, especially just above the r-process peaks. Neutrino interactions however can also significantly affect the heavy $Z > 70$ abundances. This is because neutrino capture on neutrons can increase $Y_e$ and decrease the neutron to seed ratio.

### 3.4.2 Exponential model

Results for the exponential models are shown in Fig. 3. If the dynamical timescale becomes longer than around 1.5 seconds, the yields begin to differ from the universal pattern. The longest dynamical timescale case shows a different pattern even for $56 < Z < 70$ elements. It also shows a Eu isotopic ratio which is inconsistent with the observed values. These differences relate to the fact that near freezeout neutron captures are in competition with beta decay in these models. Hence, the $r$-process path at neutron capture freeze out is different. As discussed below, if we could resolve nuclear physics uncertainties, the observed abundance distribution might discriminate between short and long timescale astrophysical sites for the $r$-process.
3.5 Analysis of universality

Both observations and our theoretical calculations indicate that the observed universality of the $r$-process does not imply a unique astrophysical site for $r$-process nucleosynthesis. That is, a variety of conditions can lead to the same observed universal abundance distribution in the $56 < Z < 75$ region. The reason for the universality of the $60 \leq Z \leq 75$ elements can be traced to the fact that there are no significant nuclear shell closures along the $r$-process path for the progenitor nuclides of these elements. The $r$-process path corresponding to $(n, \gamma) \rightleftharpoons (\gamma, n)$ equilibrium essentially flows along a fixed neutron separation energy given approximately as

$$S_n = \frac{T_9}{5.040} \times \{34.075 - \log(Y_n \times \rho) + 1.5 \times \log(T_9)\} \text{ MeV},$$

(10)

where $\rho$ is the mass density of material in units of g cm$^{-3}$, $T_9$ is the temperature in units of $10^9$ K, and $Y_n$ is the neutron number fraction. In the models shown on Figures 1a-d, there are no waiting points for the progenitors of $56 < Z < 75$ elements. The progenitor nuclei have larger neutron capture cross sections. Hence $(n, \gamma) \rightleftharpoons (\gamma, n)$ equilibrium is maintained longer for these elements. Moreover, for a variety of astrophysical conditions the $r$-process path at freezeout is so far from stability that the final abundance distribution is dominated by the effects of beta-delayed neutron emission which leads to the same universal curve.

4 Cosmochronometry

4.1 Th/Eu chronometer

Our theoretical calculations show that the ratio of Th to Eu (or to any other stable $r$-process nuclei for $56 < Z < 75$) is strongly dependent upon the nucleosynthesis environment. Table 1 summarizes Th/Eu ratios calculated in different environments most of which reproduce the observed universality and have initial Th/Eu ratios greater than that presently observed in CS22892-052. These Th/Eu ratios vary by almost two orders of magnitude rendering an uncertainty in the inferred ages of at least a factor of 2.

To estimate the age of a metal deficient star using the Th/Eu chronometer, one must therefore unambiguously identify the astrophysical site at which they were generated. This is particularly true for the oldest metal-poor stars whose initial composition is likely to have been enriched by only a single supernova
event. The details of that particular supernova event are likely to be different from one metal poor star to another. Therefore, it is dangerous to estimate the ages of metal deficient stars using the Th/Eu ratio. One cannot predict the initial Th/Eu production ratio without identifying its nucleosynthesis environment. We note, however, that the sensitivity of light-element abundances and Pb to parameters (e.g. Fig. 1d) might be used to help identify this environment.

4.2 U/Th chronometer

On the other hand, because Th and U are neighboring actinide nuclei, and because both are the result of an extensive alpha decay chain (Cowan, Thielemann, and Truran 1991), one would anticipate that some of the above model dependence for this chronometric pair might be removed. We have studied various models of different entropy, $Y_e$, and freezeout temperature under the constraint that the abundances of $56 < Z < 75$ elements be consistent with the observational results, and also that the initial production ratio of Th and U to Eu should be significantly larger than the presently observed value in CS22892-052 of $\log(\text{Th/Eu}) = -0.66 \pm 0.08$ (Cowan et al 1999).

Table 1 summarizes various models. Three of the models shown in Figures 1-3 are ruled out by these criteria. The ratio of $^{238}\text{U}/^{232}\text{Th}$ for each of these models is given. It is particularly noteworthy that all models yield almost the same value of the U/Th ratio even though the Th/Eu ratios are vastly different. These representative models all lead to a production ratio of $U/Th = 0.40 \pm 0.05$ ($1\sigma$). Thus, our calculations indicate that U and Th are nearly always generated in the same ratio as long as enough Th and U are generated to be consistent with the observed abundances. Since the stellar age only depends logarithmically of the production ratio by Eq. 1, this is sufficiently accurate to determine the stellar age to ±14% or about ±2 Gyr.

Hence, the U to Th production ratio does not particularly depend upon details of the nucleosynthesis environment. Using this chronometer, one can, therefore, estimate the age of metal deficient stars without much astrophysical uncertainty. Unfortunately, the U to Th ratio does, however, depend upon nuclear theoretical models [e.g. Goriely & Arnold (2001)], i.e. mass formulae, beta-decay rates, alpha-decay rates, and particularly $\beta^-$-delayed fission and neutron emission (Meyer et al., 1989). We are presently conducting a separate study of the dependence of this ratio on the input nuclear physics.
Fig. 1. Dependence of the nucleosynthesis yields upon various parameters of the astrophysical environment (see Table 1). Closed circles show observed elemental abundances in CS22892-052 (Sneden et al., 2000). In (a) the entropy per baryon for each model is \( S/k = 400, 350, 300, \) and 250 as labeled, and the dynamical time scale is fixed at 0.005 sec. In (b) the asymptotic temperature is 0.4, 0.6, 0.8 in units of \( T_9 \) as labeled. In (c) dynamical time scales of 0.015, 0.010, and 0.005 sec are shown for fixed \( S=400 \) and \( Y_e=0.45 \). In (d) the electron fraction is varied. (See Table 1 for details.)

Fig. 2. Dependence of yields upon neutrino luminosity.
Fig. 3. Dependence of the yields upon timescale. If the timescale becomes longer than 1.5 second, the universal pattern is broken.

Table 1
U/Th, Th/Eu, and parameters for various models shown in Figures 1 - 3

| S/k | $T_b(T_0)$ | $\tau_{\text{dyn}}$ (sec) | $Y_e$ | U/Th | Th/Eu | fr(Eu$^{151}$) | $L_{\nu}$ ergs/sec | Figure |
|-----|------------|--------------------------|------|------|-------|----------------|-----------------|--------|
| 400 | 0.4        | 0.005                    | 0.45 | 0.51 | 13.5  | 0.53           | $10^{51}$       | 1(b),1(c) |
| 400 | 0.6        | 0.005                    | 0.45 | 0.38 | 1.5   | 0.51           | $10^{51}$       | 1(a),1(b),1(d),2 |
| 350 | 0.6        | 0.005                    | 0.45 | 0.37 | 0.95  | 0.52           | $10^{51}$       | 1(a)    |
| 300 | 0.6        | 0.005                    | 0.45 | 0.37 | 0.51  | 0.52           | $10^{51}$       | 1(a)    |
| 250 | 0.6        | 0.005                    | 0.45 | 0.36 | 0.20  | 0.52           | $10^{51}$       | 1(a)    |
| 400 | 0.8        | 0.005                    | 0.45 | 0.26 | 0.0011| 0.47           | $10^{51}$       | 1(b)    |
| 400 | 0.4        | 0.01                     | 0.45 | 0.40 | 1.3   | 0.54           | $10^{51}$       | 1(c)    |
| 400 | 0.4        | 0.015                    | 0.45 | 0.27 | 0.045 | 0.54           | $10^{51}$       | 1(c)    |
| 400 | 0.6        | 0.005                    | 0.35 | 0.39 | 1.5   | 0.52           | $10^{51}$       | 1(d)    |
| 400 | 0.6        | 0.005                    | 0.40 | 0.40 | 0.21  | 0.52           | $10^{51}$       | 1(d)    |
| 400 | 0.6        | 0.005                    | 0.45 | 0.58 | 6.0   | 0.49           | $10^{50}$       | 2        |
| 250 | 0.6        | 0.005                    | 0.45 | 0.54 | 0.48  | 0.49           | 0              | 2        |
| 400 | 0.6        | 0.5                      | 0.3  | 0.51 | 3.8   | 0.47           | 0              | 3        |
| 400 | 0.6        | 1.0                      | 0.1  | 0.43 | 7.0   | 0.55           | 0              | 3        |
| 400 | 0.6        | 1.5                      | 0.1  | 0.50 | 0.0027| 0.35           | 0              | 3        |

5 Conclusion and discussion

Our theoretical calculations indicate that the coincidence of the observed abundance distribution for $56 < Z < 75$ elements with the Solar r-process
abundances does not necessarily mean that all $r$-process events occur in the same universal environment. Moreover, different abundance distributions for $Z \geq 75$ and $Z \leq 56$ elements are produced even when the universal $56 < Z < 75$ abundances are reproduced. Hence, it is not possible to predict the initial production ratio of Th to Eu in each metal deficient star without somehow independently identifying each production environment. We therefore conclude that there is substantial uncertainty when using the Th/Eu chronometer to estimate the ages of metal deficient stars.

We note that the reason for the uncertainty is that in realistic (e.g. SN wind) $r$-process models, one tends to run out of neutrons as actinide elements are being formed. It might be possible, however, that an $r$-process environment could occur in which there were abundant neutrons present as the actinide nuclei are synthesized. In this case, the $r$-process could proceed to the fission termination and recycling. If most stars experienced this, then the uncertainty in the Th/Eu chronometer would be reduced and the CS31082-001 star would be an interesting exception. Nevertheless, since it is difficult to produce fission recycling in realistic (e.g. wind) models, we caution against this assumption. Another possibility to reduce the Th/Eu uncertainty is that a combination of light-element ($Z \leq 56$) abundances and Pb-region abundances (Schatz et al., 2002) might help to identify the environment. We also note that variations of the light-element abundances are quite natural in neutrino-driven wind models even when a universality of heavier elements is imposed. Hence, one may not need to propose two different $r$-process sites (Qian & Wasserburg, 2000) to account for the variations of light elements relative to the universal heavy nuclei. Although two sites are probably still necessary to explain the meteoritic evidence. To some extent, however, the light-element abundances may simply reflect the star-to-star variations in a single neutrino-driven wind scenario for the $r$-process.

On the other hand, we find that the U/Th chronometer is a robust means to estimate the cosmic age. From our theoretical calculations, we have shown that the U/Th initial production ratio is almost independent of the nucleosynthesis environment as suggested by Goriely & Arnold (2001) and Wanajo et al. (2002). Indeed, the present work vindicates the conclusions of those papers for wider range of astrophysical environments. Hence, using this chronometer, one can estimate the age of metal deficient stars with little correction for the astrophysical uncertainties. Unfortunately, some uncertainty due to the nuclear physics still remains (e.g. Schatz et al., 2002). Further quantitative studies of the uncertainties due to various nuclear physics input such as the mass formula, beta-decay rates, alpha-decay rates, $\beta$-delayed fission and neutron emission are strongly desired. Efforts along this line are currently underway.

Regarding the universal abundance curve, we have shown that there is a dependence of the $56 < Z < 70$ abundances on the dynamical time scale. We
also note that there is a dependence of these abundances on the detailed nuclear physics models. The hope is that with sufficiently precise observed abundances one might be able to both identify the true dynamical timescale and the correct nuclear physics models for the r-process. More accurate observational data are likely to be available in the future due to the development of large aperture telescopes and high resolution spectroscopy. Clearly, more observations of r-process abundances in metal poor stars are desired.

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