Europium production: neutron star mergers versus core-collapse supernovae

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ABSTRACT

We have explored the Eu production in the Milky Way by means of a very detailed chemical evolution model. In particular, we have assumed that Eu is formed in merging neutron star (or neutron star-black hole) binaries as well as in Type II supernovae. We have tested the effects of several important parameters influencing the production of Eu during the merging of two neutron stars, such as (i) the time-scale of coalescence, (ii) the Eu yields and (iii) the range of initial masses for the progenitors of the neutron stars. The yields of Eu from Type II supernovae are very uncertain, more than those from coalescing neutron stars, so we have explored several possibilities. We have compared our model results with the observed rate of coalescence of neutron stars, the solar Eu abundance, the [Eu/Fe] versus [Fe/H] relation in the solar vicinity and the [Eu/H] gradient along the Galactic disc. Our main results can be summarized as follows: (i) neutron star mergers can be entirely responsible for the production of Eu in the Galaxy if the coalescence time-scale is no longer than 1 Myr for the bulk of binary systems, the Eu yield is around $3 \times 10^{-7} M_{\odot}$ and the mass range of progenitors of neutron stars is 9–50 $M_{\odot}$; (ii) both Type II supernovae and merging neutron stars can produce the right amount of Eu if the neutron star mergers produce $2 \times 10^{-7} M_{\odot}$ per system and Type II supernovae, with progenitors in the range 20–50 $M_{\odot}$, produce yields of Eu of the order of $10^{-8}$–$10^{-9} M_{\odot}$; (iii) either models with only neutron stars producing Eu or mixed ones can reproduce the observed Eu abundance gradient along the Galactic disc.

Key words: nuclear reactions, nucleosynthesis, abundances – Galaxy; abundances – Galaxy: evolution.

1 INTRODUCTION

Approximately half of the elements beyond the iron peak are formed through rapid neutron captures in stars (r-process; Burbidge et al. 1957). ‘Rapid’ refers to the time-scale of the process relative to the $\beta$-decay rates of the unstable nuclei. Although detailed evaluations of the mechanisms of r-process nucleosynthesis have long since been made (Burbidge et al. 1957; Seeger, Fowler & Clayton 1965), the dominant production site of the r-process elements has not yet been unambiguously identified (see e.g. Thielemann et al. 2010).

The challenge of identifying the main astrophysical r-process site consists in meeting the various constraints coming from measurements of abundances in Galactic stars, from the modelling of possible sources such as supernovae (SNe) and neutron star (NS) mergers, from nuclear physics and, last but not least, from detailed Galactic chemical evolution studies. Observations of heavy element abundances in Galactic halo stars provide important constraints on the astrophysical site(s) of r-process nucleosynthesis. Early recognition that the heavy elements abundance patterns in Galactic halo stars provide important constraints on the astrophysical site(s) of r-process nucleosynthesis. Early recognition that the heavy elements abundance patterns in Galactic halo stars provide important constraints on the astrophysical site(s) of r-process nucleosynthesis. Early recognition that the heavy elements abundance patterns in Galactic halo stars provide important constraints on the astrophysical site(s) of r-process nucleosynthesis. Early recognition that the heavy elements abundance patterns in Galactic halo stars provide important constraints on the astrophysical site(s) of r-process nucleosynthesis.

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also by Froehlich et al. (2006a,b) as well as Pruet et al. (2005, 2006). Recently, hydrodynamical simulations with accurate neutrino transport have shown that the neutrino winds are proton rich (Arcones, Janka & Scheck 2007; Fischer et al. 2010; Hüdepohl et al. 2010) or slightly neutron rich (Martínez-Pinedo et al. 2012; Roberts et al. 2012), but never very neutron rich, as found in older simulations (e.g. Takahashi et al. 1994; Woosley et al. 1994). This casts serious doubts on the validity of the neutrino wind scenario. It seems now established that neutrino-driven winds from proto-NS cannot be the main origin of the r-process elements beyond \( A \approx 110 \) (Arcones & Thielemann 2013; Wanajo 2013). On the other hand, prompt explosions of massive stars in the 8–10 \( M_\odot \) range may lead to an ejected amount of r-process matter consistent with the observed Galactic abundances (Wheeler, Cowan & Hillebrandt 1998). Yet, it is not clear whether these prompt explosions do occur. Recent 3D magnetohydrodynamical investigations point to SN progenitors characterized by high rotation rates and large magnetic fields as an interesting site for the strong r-process observed in the early Galaxy (Winteler et al. 2012, and references therein). In this context, the rarity of progenitors with the required initial conditions would also provide a natural explanation for the scatter in the abundances of r-process elements observed for low-metallicity stars. This r-process element production channel certainly deserves further investigation.

Another major source of r-process elements might be NS mergers (Lattimer & Schramm 1974, 1976; Lattimer et al. 1977; Freiburghaus, Rosswog & Thielemann 1999; Goriely, Bauswein & Janka 2011; Roberts et al. 2011). The resulting abundance patterns are extremely robust with respect to varying the parameters of the merging binary system, and the results from a double NS and a NS black hole merger are Practically indistinguishable, see, for example, fig. 4 in Korobkin et al. (2012). Therefore, we refer to both types of systems collectively as compact binary mergers (CBM).

Rosswog et al. (1999, 2000) and more recently Oechslin, Janka & Marek (2007), Bauswein, Goriely & Janka (2012), Rosswog (2013), Kotakezaka et al. (2013) and Kurokata, Ioka & Shibata (2013) showed that up to \( 10^{-2} \) \( M_\odot \) of r-process matter may be ejected in a single coalescence event. Though this quantity is orders of magnitude higher than the average r-process ejecta required from Type II SNe (SNII), if every SNII is expected to produce r-process matter, the rate of CBM in the Galaxy is significantly lower than the SNII rate, making unclear which of the sources could potentially be the major r-process element producer. NS mergers could also provide a natural explanation for the scatter of r-process element abundances at low metallicity, given their rarity and high r-process element production.

In principle, chemical evolution studies offer a way to discriminate among different sites for the r-process element production, through the comparison of model predictions with the observations. Unfortunately, different studies have reached different conclusions (e.g. Ishihara & Wanajo 1999; Travaglio et al. 1999; De Donder & Vanbeveren 2003; Argast et al. 2004; Cescutti et al. 2006). Furthermore, only rarely all the possible r-process element sources have been screened in the very same study. In particular, Argast et al. (2004) analysed the possibilities of r-process production from SNII and CBM, and concluded that it is unlikely that CBM can be responsible for the entire r-process production, because of the delayed Eu appearance predicted by their model, which would not allow us to reproduce the Milky Way data at low metallicity. This was due to the adoption of an inhomogeneous chemical evolution model, dropping the instantaneous mixing approximation (I.M.A.) in the early Galactic evolutionary phases. This model was predicting the spread for r-process elements at low metallicity but also for other elements which do not show a large spread. On the other hand, De Donder & Vanbeveren (2003) had concluded that NS/black hole mergers could be responsible for the Galactic r-process production, but they did not consider the possible contribution from SNeII. Their model assumed I.M.A.

In this paper, we intend to study again the problem of r-process production in the Galaxy and in particular of europium, in the light of recent and detailed nucleosynthesis calculations of r-process production in CBM (Korobkin et al. 2012), as well as of the existence of new detailed data. We will explore the possibility of Eu production from SNII and CBM with the intent of establishing which one of the two sources is the most likely and what are the shortcomings of both scenarios. We will adopt a very recent detailed chemical evolution model for the Milky Way including updated stellar yields and reproducing the majority of the observational constraints. We will also predict the expected Eu gradient along the Galactic disc. This paper is organized as follows. In Section 2, we describe the chemical evolution model. In Section 3, we show the adopted Eu nucleosynthesis prescriptions for the CBM and SNII, as well as the computation of the CBM rate. In Section 4, the results are presented, and in Section 5, the main conclusions are summarized.

2 THE CHEMICAL EVOLUTION MODEL

We adopted the model 15 of Romano et al. (2010), which contains updated stellar yields and reproduces the majority of the [X/Fe] versus [Fe/H] relations observed in Galactic stars in the solar vicinity. This model is an updated version of the Chiappini, Matteucci & Gratton (1997) and Chiappini, Matteucci & Romano (2001) two-infall model, where it is assumed that the inner halo and part of the thick disc formed by means of a gas accretion episode independently from the thin disc, which formed by means of another gas accretion episode on a much longer time-scale. This model relaxes the instantaneous recycling approximation, i.e. the stellar lifetimes are taken into account in detail, but retains I.M.A., i.e. the stellar ejecta are assumed to cool and mix instantaneously with the surrounding interstellar medium (ISM). The model does not consider Galactic fountains, but see Spitoni et al. (2009), who showed that the fountains should not affect the chemical abundances in the disc, as long as the process is shorter than 100 Myr, and do not allow for gas recycling through the hot halo (but see e.g. Brook et al. 2013). In the Spitoni et al. (2009) paper it was shown that the effect of the fountains is also to delay the chemical enrichment, thus breaking the I.M.A. However, it was found that even a delay of several hundred million years would not change the chemical results for the evolution of the Galactic disc, thus supporting I.M.A. On the other hand, inhomogeneities in the ISM could be important in the early evolutionary phases, during halo formation. In this respect, there are conflicting results: on one hand a very little spread in abundance ratios of many elements down to [Fe/H] = −4.0 dex is found, on the other hand a large spread is observed in abundance ratios involving s- and r-process elements relative to Fe. In fact, the data for europium show a large spread at low metallicities: the interpretation of this spread, however, can be related more to the different stellar producers of these elements rather than to a less efficient mixing (see Cescutti et al. 2006, 2013), since in this latter case, the spread should be seen for all chemical species. In summary, we think that I.M.A. is not a bad assumption on the scale of the solar vicinity also because, besides the above-mentioned results of Spitoni et al. (2009), it has been shown (Recchi, Matteucci & D’Ercole 2001) that mixing in the ISM can occur on very short time-scales of the order of tens of million years.
The following equation describes the evolution of the surface mass density of the gas in the form of the generic element $i$, $\sigma_i(r, t)$:

$$\sigma_i(r, t) = -\psi(r, t) X_i(r, t)$$

$$+ \int_{M_{bh}}^{B_{BH}} \frac{\psi(r, t - \tau_m) Q_{mi}(t - \tau_m) \phi(m) \, dm}{\mu}$$

$$+ A_{i1} \int_{M_{BH}}^{B_{BH}} \phi(M_b) \cdot$$

$$\left[ \int_{\mu_{in}}^{0.5} \frac{f(\mu) \psi(r, t - \tau_m) Q_{mi}^{SNII}(t - \tau_m) \, d\mu}{\phi(m)} \right] \, dM_b$$

$$+ (1 - A_{i1}) \int_{M_{BH}}^{B_{BH}} \frac{\psi(r, t - \tau_m) Q_{mi}(t - \tau_m) \phi(m) \, dm}{\mu}$$

$$+ \int_{M_{1}}^{M_{BH}} \psi(r, t - \tau_m) Q_{mi}(t - \tau_m) \phi(m) \, dm$$

$$+ X_{A_i} A_i(r, t),$$

where $X_i(r, t)$ is the abundance by mass of the element $i$ at the time $t$ and Galactic radius $r$, $Q_{mi}$ indicates the fraction of mass restored by a star of mass $m$ in the form of the element $i$, the so-called production matrix as defined by Talbot & Arnett (1973). The upper mass limit, $Q_{mi}(t)$, is set to 100 $M_\odot$, while $M_1$, the lightest mass which contributes to the chemical enrichment, is set to 0.8 $M_\odot$. The parameter $A_{i1} = 0.035$ represents the fraction of binary systems with the right characteristics to give rise to SNeIa in the initial mass function (IMF); its value is chosen in order to obtain the best fit to the present-time SNeIa rate. The adopted progenitor model for SNeIa is the single-degenerate model as suggested by Greggio & Renzini (1983) and later repoposed by Matteucci & Recchi (2001). This formulation, which is different from single-degenerate rates computed by means of population synthesis models (e.g. Mennelens et al. 2010), has proven to be successful in reproducing the chemical evolution of the Milky Way, as well as of other galaxies, such as ellipticals. This rate is also very similar to the rate derived from the double-degenerate model (see Greggio 2005), and the two rates produce the same chemical evolution results, as shown in Matteucci et al. (2006, 2009), where the interested reader can find more details. In other words, from the point of view of chemical evolution, using the single- or double-degenerate model or a combination of the two does not produce any noticeable effect in the chemical results.

The term $A_i(r, t)$ represents the gas accretion rate:

$$A_i(r, t) = a(r) e^{-t_{hi}^{(r)}} + b(r) e^{-(t - t_{max}^{(r)})/t_{hi}^{(r)}}$$

$$+ \int_{M_{BH}}^{B_{BH}} \psi(r, t - \tau_m) Q_{mi}(t - \tau_m) \phi(m) \, dm$$

$$+ X_{A_i} A_i(r, t),$$

where $X_{A_i}$ are the abundances in the infalling material, which is assumed to be primordial, and are set after Romano et al. (2006), while $t_{max}^{(r)} = 1$ Gyr is the time for maximum infall on to the thin disc, $t_{hi}^{(r)} = 0.8$ Gyr is the time-scale for the formation of the inner halo/thick disc and $t_{hi}^{(r)}$ is the time-scale for the formation of the thin disc and is a function of the Galactocentric distance (inside-out formation; Matteucci & François 1989; Chiappini et al. 2001; Pilkington et al. 2012). In the framework of our model, for the solar neighbourhood, the best value is $t_{hi}^{(r)} = 7$ Gyr (see Chiappini et al. 1997; Romano et al. 2010). The quantities $a(r)$ and $b(r)$ are parameters fixed by reproducing the present-time total surface mass densities in the halo and disc of the Galaxy (see Romano et al. 2000 for details).

The adopted IMF, $\phi(m)$, is that of Scalo (1986) and the stellar lifetimes are taken from Schaller et al. (1992). The assumed star formation rate (SFR), $\psi(r, t)$, is a Schmidt–Kennicutt law proportional to the surface gas density to the 1.5th power.

The model computes in detail the chemical abundances of 37 species in the ISM. For all elements but europium, the adopted stellar yields, which are used to compute the entries of the $Q_{mi}$ matrix, are described in detail in Romano et al. (2010). They reproduce very well the abundance patterns of most chemical species observed in the stars of the Milky Way halo (see also Brusadin, Matteucci & Romano 2013) and discs (Micali, Matteucci & Romano 2013).

In the following, we review a few basic facts.

(i) Low- and intermediate-mass stars ($m = 0.8–8$ $M_\odot$) contribute mainly to the chemical enrichment in He, C, N, s-process elements and, perhaps, some $^7$Li and Na. The adopted stellar yields are from Karakas (2010) and rest on detailed stellar evolutionary models.

(ii) Massive stars ($m > 8$ $M_\odot$) are responsible for the production of the $\alpha$- and iron-peak elements. The production of (primary) nitrogen and s-process elements is boosted at low metallicity in fast stellar rotators (Meynet & Maeder 2002a; Frischknecht, Hirschi & Thielemann 2012). Here, we adopt He, C, N and O yields from pre-SN models of rotating massive stars from Meynet & Maeder (2002b), Hirschi, Meynet & Maeder (2005), Hirschi (2007) and Ekström et al. (2008). For heavier elements, yields are from Kobayashi et al. (2006).

(iii) When in binary systems with the right characteristics to give rise to SNeIa events, white dwarfs (originating from low- and intermediate-mass stars) are responsible for the production of the bulk of iron in the Galaxy. The adopted SNeIa yields are those of Iwamoto et al. (1999, their model W7).

In the next section, we discuss how europium production from stars has been implemented in our model.

3 EUROPIUM PRODUCTION SITES

As discussed in the introduction, two possible sites have been suggested for the production of Eu in stars: SNeII of either low (8–10$M_\odot$) or high mass (>20$M_\odot$) Cowan, Thielemann & Truran 1991; Woosley et al. 1994; Wanajo et al. 2001) and CBM (Lattimer & Schramm 1974; Eichler et al. 1989; Freiburghaus et al. 1999; Rosswog et al. 1999, 2000). However, the classical site for the production of r-process elements, namely SNeIa, has been recently questioned (e.g. Arcones et al. 2007), while the r-process production in CBM seems a very robust result (e.g. Korobkin et al. 2012). We have computed the evolution of the Eu abundance in the Milky Way under several assumptions: (i) Eu is produced only in CBM; (ii) Eu is produced only in SNII explosions and (iii) Eu is produced both in CBM and SNII explosions.

3.1 Europium production from CBM

To include the production of Eu from coalescence of NS, our Galactic chemical evolution model, we need to define the following quantities:

(i) the realization probability for CBM, $\alpha_{CBM}$;
(ii) the time delay between the formation of the double NS system and the merging event, $\Delta t_{CBM}$;
(iii) the amount of Eu produced during the merging event, $M_{Eu}^{CBM}$.

Coalescence of a black hole and an NS may work as well.
In our model, the rate of CBM at the time \( t \) is computed under the assumption that the rate of formation of double NS systems, which will eventually coalesce, is a fraction \( \alpha_{\text{CBM}} \) of the NS formation rate at the time \( t - \Delta t_{\text{CBM}} \):

\[
R_{\text{CBM}}(t) = \alpha_{\text{CBM}} \cdot \int_{M_{\text{sl},1}}^{M_{\text{sl},2}} \psi(t - \tau_m - \Delta t_{\text{CBM}}) \phi(m) \, \text{d}m,
\]

(3)

where \( M_{\text{sl},1} = 9 \) and \( M_{\text{sl},2} = 30 \, M_\odot \) are the canonical lower and upper masses, at birth, which can leave an NS as a remnant (we will come back to the issue of the choice of the upper mass limit in Sections 4 and 5). Stars with \( m > 30 \, M_\odot \) probably leave black holes as remnants, but the situation is quite uncertain and depends on the assumed rate of mass-loss in massive stars and its dependence upon stellar metallicity (e.g. Meynet & Maeder 2002a,b). The value of the parameter \( \alpha_{\text{CBM}} \) is chosen by imposing that equation (3) reproduces the present-time rate of NS merging in the Galaxy. Several observational estimates of this rate appeared in the literature (van den Heuvel & Lorimer 1996; Kalogera & Lorimer 2000; Belczynski, Kalogera & Bulik 2002; Kalogera et al. 2004). Here, we take that of Kalogera et al. (2004), \( R_{\text{CBM}}(t_{\text{now}}) = 83^{+309}_{-11} \, \text{Myr}^{-1} \) and find \( \alpha_{\text{CBM}} = 0.018 \).

### 3.1.2 The time delay

Based on the energy/angular momentum loss to gravitational waves (Peters & Mathews 1964), inspiral times are usually thought to be between 10 and 100 Myr, though some studies (e.g. Belczynski et al. 2002) find that a large fraction of systems would merge within less than 1 Myr. Argast et al. (2004), in a work similar to ours, considered two different time-scales: 1 and 100 Myr. Here, we will consider 1, 10 and 100 Myr. It is worth noting that in both this work and Argast et al. (2004), it is assumed that all NS binaries have the same coalescence time-scale. Clearly, a more realistic approach would consider a distribution function of such time-scales, in analogy with SNeIa for which a distribution for the explosion times is defined (see Greggio 2005).

### 3.1.3 The Eu yields

Every NS merging event is assumed to produce the same amount of EU since we consider only \( 1.4+1.4 \, M_\odot \) systems. In the literature there have been different EU yields reported: Rosswog et al. (1999, 2000) found that up to \( 10^{-3} \, M_\odot \) of r-process material are ejected per event and they pointed out that this would be enough to be a major contribution to the cosmic r-process inventory. A number of recent studies (Oechslin et al. 2007; Bauswein et al. 2013; Hotokezaka et al. 2013; Kyutoku et al. 2013; Rosswog 2013) find a spread of ejecta masses in this range with the exact numbers, around the value of \( 10^{-2} \), depending on the binary mass ratio and to some extent on the employed physics. We take the value of \( \sim 0.01 \, M_\odot \) and assume that the mass of Eu is in the range \( M_{\text{Eu}}^{CBM} = 10^{-5} - 10^{-7} \, M_\odot \), where the lower value is probably the most realistic one. In particular, we compute models (see Table 1) assuming different values for the EU yield: \( M_{\text{Eu}}^{CBM} = 10^{-7}, 2 \times 10^{-7}, 3 \times 10^{-7} \) and \( 9 \times 10^{-7} \, M_\odot \).

### 3.2 Europium production from core-collapse SNe

The yields of r-process elements and therefore of Eu from SNeII are highly uncertain. Cescutti et al. (2006) suggested some empirical EU yields dictated by the need of reproducing the trend of \([\text{Eu/Fe}]\) versus \([\text{Fe/H}]\) observed for Galactic stars. They suggested that Eu is a pure r-process element and that it is produced in the mass range \( 12–23 \, M_\odot \). In particular, according to Cescutti et al. (2006), a \( 12 \, M_\odot \) star must produce \( M_{\text{Eu}}^{\text{SN}} = 4.5 \times 10^{-8} \, M_\odot \); a \( 15 \, M_\odot \) star, \( M_{\text{Eu}}^{\text{SN}} = 3.0 \times 10^{-8} \, M_\odot \) and a \( 30 \, M_\odot \) star, \( M_{\text{Eu}}^{\text{SN}} = 5.0 \times 10^{-10} \, M_\odot \). Argast et al. (2004) adopted somewhat different empirical yields: they considered either the lower mass SNeII (8–10 \( M_\odot \)) or the higher mass SNeII (20–50 \( M_\odot \)) as dominant r-process sites. In this paper, we show the results of our model adopting either the yields from Cescutti et al. (2006) or the yields from Argast et al. (2004); their model SN2050, modified as in Mod2SN in the mass range 20–50 \( M_\odot \).

### Table 1. Model parameters.

<table>
<thead>
<tr>
<th>Model</th>
<th>( \Delta t_{\text{CBM}} ) (Myr)</th>
<th>( M_{\text{Eu}}^{\text{CBM}} ) (M(_\odot))</th>
<th>Yields from SNeII</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mod1NS</td>
<td>100</td>
<td>( 10^{-7} )</td>
<td>–</td>
</tr>
<tr>
<td>Mod2NS</td>
<td>10</td>
<td>( 10^{-7} )</td>
<td>–</td>
</tr>
<tr>
<td>Mod3NS</td>
<td>1</td>
<td>( 10^{-7} )</td>
<td>–</td>
</tr>
<tr>
<td>Mod1NS’</td>
<td>100</td>
<td>( 3 \times 10^{-7} )</td>
<td>–</td>
</tr>
<tr>
<td>Mod2NS’</td>
<td>10</td>
<td>( 3 \times 10^{-7} )</td>
<td>–</td>
</tr>
<tr>
<td>Mod3NS’</td>
<td>1</td>
<td>( 9 \times 10^{-7} )</td>
<td>–</td>
</tr>
<tr>
<td>Mod1SN</td>
<td>–</td>
<td>–</td>
<td>Cescutti et al. (2006)</td>
</tr>
<tr>
<td>Mod2SN</td>
<td>–</td>
<td>–</td>
<td>Argast et al. (2004)</td>
</tr>
<tr>
<td>Mod3SN</td>
<td>–</td>
<td>–</td>
<td>Cescutti et al. (2006)</td>
</tr>
<tr>
<td>Mod1NSNS</td>
<td>1</td>
<td>( 10^{-7} )</td>
<td>Cescutti et al. (2006)</td>
</tr>
<tr>
<td>Mod2NSNS</td>
<td>10</td>
<td>( 2 \times 10^{-7} )</td>
<td>Argast et al. (2004)</td>
</tr>
</tbody>
</table>

\( a \)Yields from table 2 of Argast et al. (2004), their Model SN2050, but for progenitors in the mass range 20–23 \( M_\odot \) a constant yield of \( 3.8 \times 10^{-8} \, M_\odot \) is assumed.

\( b \)Yields from Cescutti et al. (2006) in the mass range 12–15 \( M_\odot \) and from Argast et al. (2004; their model SN2050, modified as in Mod2SN) in the mass range 20–50 \( M_\odot \).
to 50 M⊙ be active on very short time-scales, such as SNeII of high mass (up to [Fe/H] ∼ 3.5 dex). This suggests that another Eu source should be active on low [Fe/H]. In any case, even if the minimum value for [Eu/Fe]t/ΔtCBM is present in the data, especially at low metallicities, our model is designed to fit the average trend. We consider two different yield sets (see Table 1, models labelled Mod1SN, Mod2SN and Mod3SN). The model with the yields from Cescutti et al. (2006) only for progenitors in the 20–23 M⊙ mass range. In fact, the kink at [Fe/H] ∼ −3.0 dex in the white curve is related to the appearance of SNeIa with progenitors of initial mass ∼ 20 M⊙. We had to reduce the Eu produced by an ∼ 20 M⊙ progenitor from 10−5 to 3.8 × 10−8 M⊙ in order to best fit the data and reduce the kink.

From the comparison of our model predictions with the observations, we deduce that the yields from SNeII should be adjusted and that the mass range of Eu producers should be extended up to 50 M⊙. This is dictated by the most recent data on [Eu/Fe] extending down to [Fe/H] ≤ −4.0 dex. Cescutti et al. (2006) had derived the range 12–30 M⊙ for Eu producers, by comparison with older data and by adopting different Fe yields from massive stars than in this paper. In particular, Cescutti et al. (2006) adopted the Fe yields of Woosley & Weaver (1995) for solar metallicity, whereas here we adopt the more recent yields depending on metallicity by Kobayashi et al. (2006). These latter predict a higher increase of the Fe abundance in the early Galactic phases relative to the Woosley & Weaver (1995) yields. A comparison of the Fe yields adopted in Cescutti et al. (2006) and our study is shown in Fig. 4. We also deduce that stars with masses smaller than 20 M⊙ must contribute Eu production, in order to counterbalance the production of Fe from SNeIa (see Fig. 3, white solid line). Therefore, we run a hybrid model (model Mod3SN; see Table 1 and Fig. 3, magenta line) that uses the yields from Cescutti et al. (2006), but only for progenitors in the 12–15 M⊙ mass range, and those from Argast et al. (2004) for progenitors in the 20–50 M⊙ mass range (we reduce the original yields in the 20–23 M⊙ mass range—see notes to Table 1).

The best yield should be 3 × 10−7 M⊙, which is the value that best fits the average trend of the data in Fig. 2. In fact, although a spread is present in the data, especially at low metallicities, our model is aimed at fitting the average trend.

In Fig. 3, we show the results of the three models with Eu production only from SNeII. We consider two different yield sets (see Table 1, models labelled Mod1SN, Mod2SN and Mod3SN). The model with the yields from Cescutti et al. (2006) fits reasonably well the data for [Fe/H] ≥ −2.0 dex, but it does not explain the [Eu/Fe] ratios in stars at lower metallicities. The model with the yields from Argast et al. (2004; model Mod2SN) is able to reproduce the low-metallicity data, but fails to reproduce the observations for [Fe/H] > −2.0 dex. Moreover, in order not to overproduce Eu at [Fe/H] ≤ −3.0 dex, we have to reduce the original yields in the 20–23 M⊙ mass range. In fact, the kink at [Fe/H] ∼ −3.0 dex in the white curve is related to the appearance of SNeII with progenitors of initial mass ∼ 20 M⊙. We had to reduce the Eu produced by an ∼ 20 M⊙ progenitor from 10−5 to 3.8 × 10−8 M⊙ in order to best fit the data and reduce the kink.

From the comparison of our model predictions with the observations, we deduce that the yields from SNeII should be adjusted and that the mass range of Eu producers should be extended up to 50 M⊙. This is dictated by the most recent data on [Eu/Fe] extending down to [Fe/H] ≤ −4.0 dex. Cescutti et al. (2006) had derived the range ∼ 20 M⊙ for Eu producers, by comparison with older data and by adopting different Fe yields from massive stars than in this paper. In particular, Cescutti et al. (2006) adopted the Fe yields of Woosley & Weaver (1995) for solar metallicity, whereas here we adopt the more recent yields depending on metallicity by Kobayashi et al. (2006). These latter predict a higher increase of the Fe abundance in the early Galactic phases relative to the Woosley & Weaver (1995) yields. A comparison of the Fe yields adopted in Cescutti et al. (2006) and our study is shown in Fig. 4. We also deduce that stars with masses smaller than 20 M⊙ must contribute Eu production, in order to counterbalance the production of Fe from SNeIa (see Fig. 3, white solid line). Therefore, we run a hybrid model (model Mod3SN; see Table 1 and Fig. 3, magenta line) that uses the yields from Cescutti et al. (2006), but only for progenitors in the 12–15 M⊙ mass range, and those from Argast et al. (2004) for progenitors in the 20–50 M⊙ mass range (we reduce the original yields in the 20–23 M⊙ mass range—see notes to Table 1).
This model reproduces very well the data over the full metallicity range.

In Fig. 5, we show the results of the models with contributions to Eu synthesis from both SN II and CBM. Model Mod1SNNS assumes the SN II yields from Cescutti et al. (2006) and the lowest Eu production from CBM ($10^{-7}\,M_\odot$) with a time delay of 1 Myr (see Table 1). Also in this case, like for the models presented in Fig. 2, we can say that the minimum coalescence time-scale (1 Myr) is required to fit the data, but still unsuited to reproduce the data for very low metallicity stars. Model Mod2SNNS assumes modified Eu yields for SNe from Argast et al. (2004); the adopted Eu yield from CBM is slightly higher than in model Mod1SNNS ($2 \times 10^{-7}\,M_\odot$), while the coalescence time-scale is longer (10 Myr). It is shown that the joint contribution to Eu synthesis from both high-mass SNe II and CBM (whose progenitors are in the range 9–30 $M_\odot$) guarantees a good fit to the available data across the full metallicity range.

In Table 2, we list the predicted Eu and Fe solar abundances by mass from the various models. They correspond to the abundances in the ISM 4.5 Gyr ago. The observed values for the Eu and Fe solar abundances are $X_{\text{Eu}} = 3.5 \times 10^{-10}$ and $X_{\text{Fe}} = 1.34 \times 10^{-3}$, respectively (Asplund et al. 2009). Most of the models predict Eu solar abundances in agreement with the observed one.

4.1 The mass range for NS progenitors

Since in all the previous models we fixed the maximum mass giving rise to an NS to be $30\,M_\odot$ and this value is quite uncertain, we decided to try to change this upper limit. In Fig. 6, we show the effect on model predictions of a different choice of the upper mass limit for NS formation in equation (3), namely $50\,M_\odot$, rather than $30\,M_\odot$. It is shown that in this case CBM alone can, in principle, account for the abundances of Eu observed in Galactic halo stars, as well as for the solar Eu (see Table 2).

4.2 Eu gradient along the Galactic disc

Finally, in Figs 7 and 8, we show the predicted gradient of Eu along the Galactic disc at the present time for a subset of models. In both figures, the data are Cepheids from Luck et al. (2011). In Fig. 7, we show cases with Eu production only by CBM. In Fig. 8, we show cases with Eu production from both NS and SN II.
Europium production

Both scenarios can account reasonably well for the observed gradient of europium in the Milky Way disc. This is because the gradient depends on the mechanism of formation of the disc, here assumed to be the inside-out one. This mechanism was suggested by Matteucci & François (1989) and proven to be valid also in semi-analytical models (e.g. Pilkington et al. 2012). What it changes in Figs 7 and 8 is the absolute value of the Eu abundance, [Eu/H], as due to the different assumptions made on the Eu producers. In this case, the models with both SNeII and CBM as Eu producers produce the best agreement with the data (see Fig. 8).

5 CONCLUSIONS AND DISCUSSION

In this paper, we have studied the production of Eu and assumed that this element can be produced in both CBM and SNeII. To do that, we have adopted a very detailed chemical evolution model which can predict the evolution of the abundances of many species and that already reproduces the behaviour of several abundances as well as the main features of the solar neighbourhood and the whole disc. Our attention has been focused here on the production of Eu by CBM and whether this production alone can explain the solar abundance of Eu as well as the [Eu/Fe] versus [Fe/H] relation. The main parameters involved in Eu production from CBM are (i) the Eu yield, (ii) the time required for the binary NS system to coalesce and (iii) the range of progenitors of NS. Among these parameters, (ii) and (iii) are quite uncertain whereas the yields seem to be more reliable.

Our main conclusions can be summarized as follows.

(i) CBM can be entirely responsible for Eu production in the Galaxy if the NS systems all have a coalescence time-scale no longer than 1 Myr, a possibility suggested by Belczynski et al. (2002), each event produces at least $3 \times 10^{-7} M_{\odot}$ of Eu and all stars with masses in the range $9–50 M_{\odot}$ leave an NS as a remnant. In this case, we can well reproduce the average trend of [Eu/Fe] versus [Fe/H] in the solar vicinity as well as the Eu solar abundance. In this case, there is no need for SNeII producing Eu. However, all the uncertainties in these parameters plus the uncertain observed rate of CBM in the Galaxy at the present time, induce some caution in drawing firm conclusions.

(ii) Perhaps, a more realistic situation would be the one where both CBM and SNeII are producing Eu. The best model in this case requires that CBM can produce $2 \times 10^{-7} M_{\odot}$ of Eu and the delay times can be various, spanning between 10 and 100 Myr. SNeII should then produce Eu in the range $20–50 M_{\odot}$ with yields of the order of $10^{58}–10^{59} M_{\odot}$ of Eu per SN. It is very important to have high stellar masses to produce the Eu observed at very low metallicity.

(iii) Both models with Eu produced only by CBM and models with CBM and SNe can reproduce the Eu abundance gradient observed along the Galactic thin disc.

Our conclusions are different from those of Argast et al. (2004), who concluded that CBM cannot be the only Eu producers. We think that this is due to the fact that Argast et al.’s model does not assume instantaneous mixing in the early Galactic evolutionary phases. This fact leads to an additional delay in the appearance of Eu in the ISM, besides the delay for the merging of the two NS, and is probably the reason why their predicted [Eu/Fe] appears at too high [Fe/H] values relative to observations. On the other hand, the assumption that the ISM was not well mixed at early times can explain the large spread observed in the r- and s-process abundances relative to Fe at low metallicity. However, such a large spread is not observed for other abundance ratios at the same metallicity. Therefore, either the spread is explained as due to different stellar producers of different elements as suggested in Cescutti et al. (2006, 2013) or the spread is related to observational errors. Inhomogeneous mixing, in fact, should act on all the elements. Our model assumes I.M.A. and therefore it cannot reproduce the observed spread but just the average trends.

On the other hand, De Donder & Vanbeveren (2003), using a model similar to this one with I.M.A., taken from Chiappini et al. (1997), and computing population synthesis binary models, explored several cases of mergers: NS/NS and NS/black hole. They concluded that mergers NS/black hole can produce enough Eu by themselves but they did not test the case of Eu production from SNeII. More recently, Mennekens & Vanbeveren (2013), adopting again a population synthesis model and a Galactic model like in De Donder & Vanbeveren (2003), reached a conclusion similar to that of this paper: the CBM can account for the entire r-process production except in the first 100 Myr, but they did not include the contribution from SNeII. Therefore, although firm conclusions on the nature of Eu cannot be yet drawn, this subject should be pursued by testing the various hypothesis discussed here in a model which takes into account early inhomogeneities as well as a distribution...
function of the delay times for the merging of NS, and that will be
the subject of a forthcoming paper.

ACKNOWLEDGEMENTS

FM and DR acknowledge financial support from PRIN MIUR 2010–11,
project ‘The Chemical and Dynamical Evolution of the Milky Way
and Local Group Galaxies’, prot. 2010LY5N2T. AA acknowledges
financial support from the Helmholtz-University Young Inv
vestigator grant no. VH-NG-825. OK and SR have been supported by
DFG grant RO-3399, AOBJ-584282 and by the Swedish Re
search Council (VR) under grant 621-2012-4870. SR has also
been supported by Compstar. Finally, we thank a highly compe
tent referee for his/her careful reading of the manuscript and useful
suggestions.

REFERENCES

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REFERENCES

Bauswein A., Goriely S., Liebendoerfer M., Mezzacappa A., Thielemann F.-K.,


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Winteler C., Käppeli R., Perego A., Arcones A., Vasset N., Nishimura N.,
Woosley S. E., Wilson J. R., Mathews G. J., Hoffman R. D., Meyer B. S.,

This paper has been typeset from a TeX/\LaTeX\ file prepared by the author.