Europium production: neutron star mergers versus core-collapse supernovae

F. Matteucci,1,2,3⋆ D. Romano,4 A. Arcones5,6, O. Korobkin7 and S. Rosswog7

1 Dipartimento di Fisica, Sezione di Astronomia, Università di Trieste, Via G.B. Tiepolo 11, I-34143 Trieste, Italy
2 INAF, Osservatorio Astronomico di Trieste, Via G.B. Tiepolo 11, I-34143 Trieste, Italy
3 INFN, Sezione di Trieste, Via A. Valerio 2, I-34127 Trieste, Italy
4 INAF, Osservatorio Astronomico di Bologna, Via Ranzani 1, I-40127 Bologna, Italy
5 Institut für Kernphysik, Technische Universität Darmstadt, Schlossgartenstraße 2, D-64289 Darmstadt, Germany
6 GSI Helmholtzzentrum fuer Schwerionenforschung GmbH, Planckstr. 1 D-64291 Darmstadt, Germany
7 The Oskar Klein Centre, Department of Astronomy, AlbaNova, Stockholm University, SE-106 91 Stockholm, Sweden

Accepted: Received; in original form 28 November 2013

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 timescale 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 identifying the main astrophysical r-process site consists in meeting the various constraints coming from measurements of abundances in Galactic stars, from the modeling of possible sources such as supernovae and neutron star 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 extremely metal-poor stars ($[Fe/H] < -3.0$ dex) involve only r-process products (Truran 1981) led to the view that r-process nucleosynthesis must be associated with the environments provided by the evolution of massive stars ($m > 10 M_\odot$). Neutrino-driven winds from proto-neutron stars following the delayed explosions of very massive stars ($m > 20 M_\odot$) have been suggested as a promising site to form the solar r-process abundances, though many shortcomings were immediately apparent with this scenario (Takahashi et al. 1994; Woosley et al. 1994; Wanajo et al. 2001). Proton-rich winds were first found by Liebendoerfer et al. (2003) and discussed in detail also by Froeichel et al. ⋆ E-mail: matteucc@oats.inaf.it

© 2013 RAS
(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 et al. 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. Woosley et al. 1994; Takahashi 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-neutron stars cannot be the main origin of the r-process elements beyond \( A \sim 110 \) (Wanajo 2013; Arcones & Thielemann 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 et al. 1998). Yet, it is not clear whether these prompt explosions do occur. Recent 3D magneto-hydrodynamics investigations point to supernova 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 elements production channel certainly deserves further investigation.

Another major source of r-process elements might be neutron star mergers (Lattimer & Schramm 1974, 1976; Lattimer et al. 1977; Freiburghaus et al. 1999; Goriely et al. 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 neutron star and a neutron star 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 et al. (2007), Bauswein et al. (2013), Rosswog (2013), Hotokezaka et al. (2013), Kyutoku et al. (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 SNeII, 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 one of the sources could potentially be the major r-process elements producer. Neutron star mergers could also provide a natural explanation for the scatter of r-process elements 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 elements production, through the comparison of model predictions with the observations. Unfortunately, different studies have reached different conclusions (e.g. Travaglio et al. 1999; Ishimaru & Wanajo 1999; De Donder & Vanbeveren 2003; Argast et al. 2004, 2006; Cescutti et al. 2006). Furthermore, only rarely all the possible r-process elements sources have been screened in the very same study. In particular, Argast et al. (2004) analysed the possibilities of r-process production from SNeII 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 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 neutron star (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 SNeII 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. The 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 SNeII, 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 et al. (1997, 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 timescale. This model relaxes the instantaneous recycling approximation (I.R.A.), 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 be affecting the chemical abundances in the disc, as long as the process is shorter than 100 Myr, and does 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 hundreds 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 it is found a very little spread in abundance ratios of many elements down to [Fe/H]=−4.0 dex, 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 et al. 2001) that mixing in the ISM can occur on very short timescales of the order of tens of million years.

The following equation describes the evolution of the sur-
face mass density of the gas in the form of the generic element \(i\), \(\sigma_i(r,t)\):

\[
\sigma_i(r,t) = -\psi(r,t)X_i(r,t)
\]

\[
+ \int_{M_{BM}}^{M_{000}} \psi(r,t - \tau_m)Q_{ma}(t - \tau_m)\phi(m)dm
\]

\[
+ A_{1a} \int_{M_{BM}}^{M_{000}} \phi(M_B)\cdot
\left[
\right.
\]

\[
\left[ 0.5 \int_{\mu_m}^{M_{BM}} \psi(r,t - \tau_m)Q_{ma}(t - \tau_m)dm\right] dM_B
\]

\[
+ (1 - A_{1a}) \int_{M_{BM}}^{M_{000}} \psi(r,t - \tau_m)Q_{ma}(t - \tau_m)\phi(m)dm
\]

\[
+ \int_{M_{BM}}^{M_{U}} \psi(r,t - \tau_m)Q_{ma}(t - \tau_m)\phi(m)dm
\]

\[
X_{A_i}A(r,t)
\]

where \(X_i(r,t)\) is the abundance by mass of the element \(i\) at the time \(t\) and Galactic radius \(r\); \(Q_{ma}\) 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, \(M_U\), is set to 100 M\(_\odot\), while \(M_L\), the lightest mass which contributes to the chemical enrichment, is set to 0.8 M\(_\odot\). The parameter \(A_{1a} = 0.035\) represents the fraction of binary systems with the right characteristics to give rise to type Ia SNe (SNeIa) in the initial mass function (IMF); its value is chosen in order to obtain the best fit to the present time SNIa rate. The adopted progenitor model for SNeIa is the single-degenerate model as suggested by Greggio & Renzini (1983) and later proposed by Matteucci & Recchi (2001). This formulation, which is different from single-degenerate rates computed by means of population synthesis models (e.g. Mennekens 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 deriving 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 \(A(r,t)\) represents the gas accretion rate:

\[
A(r,t) = a(r)e^{-t/\tau_H(r)} + b(r)e^{-(t-t_{max})/\tau_D(r)}
\]

The quantities \(X_{A_i}\) are the abundances in the infalling gas, which is assumed to be primordial, and are set after Romano et al. (2006), while \(t_{max} = 1\) Gyr is the time for maximum infall onto the thin disc, \(\tau_H = 0.8\) Gyr is the time scale for the formation of the inner halo/thick disc and \(\tau_D(r)\) is the timescale 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; Pilkingon et al. 2012). In the framework of our model, for the solar neighbourhood the best value is \(\tau_D(8\ kpc) = 7\) 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, that are used to compute the entries of the \(Q_{ma}\) 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 et al. 2013) and discs (Micali et al. 2013).

In the following, we review a few basic facts.

- 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.
- 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-supernova models of rotating massive stars from Meynet & Maeder (2002b), Hirschi et al. (2005), Hirschi (2007) and Ekström et al. (2008). For heavier elements, yields are from Kobayashi et al. (2006).
- When in binary systems with the right characteristics to give rise to SNIa 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 SNIa 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 et al. 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 SNeII, 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; iii) Eu is produced both in CBM and SNIII explosions.
3.1 Europium production from compact binary mergers

To include the production of Eu from coalescence of neutron stars\(^\dagger\) Galactic chemical evolution model we need to define the following quantities:

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

3.1.1 The neutron star merger rate

In our model, the rate of CBM at the time \(t\) is computed under the assumption that the rate of formation of double neutron star systems, which will eventually coalesce, is a fraction \(\alpha_{\text{CBM}}\) of the neutron star formation rate at the time \(t - \Delta t_{\text{CBM}}\):

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

where \(M_{\text{ns},1} = 9\) and \(M_{\text{ns},2} = 30\ M_\odot\) are the canonical lower and upper masses, at birth, which can leave a neutron star as a remnant 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 neutron star merging in the Galaxy. Several observational estimates of this rate appeared in the literature (van den Heuvel & Lorimer 1996; Kalogera & Lorimer 2000; Belczynski et al. 2002; Kalogera et al. 2004). Here, we take that of Kalogera et al. (2004), \(R_{\text{CBM}}(t_{\text{now}}) = 83^{+209}_{-66.1}\) 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 and Mathews 1964), inspiral times are usually thought to be between 10 and 100 Myrs, though some studies (e.g. Belczynski et al. 2002) find that a large fraction of systems would merge within less than a 1 Myr. Argast et al. (2004), in a work similar to ours, considered two different timescales: 1 Myr and 100 Myr. Here we will consider 1 Myr, 10 Myr and 100 Myr. It is worth noting that in both this work and Argast et al. (2004) it is assumed that all neutron star binaries have the same coalescence timescale. Clearly, a more realistic approach would consider a distribution function of such timescales, in analogy with SNeIa for which a distribution for the explosion times is defined (see Greggio 2005).

3.1.3 The Eu yields

Every neutron star merging event is assumed to produce the same amount of Eu since we consider only \(1.4\ M_\odot + 1.4\ M_\odot\) systems. In the literature there have been different Eu yields reported: Rosswog et al. (1999, 2000) found that up to \(10^{-2}\ M_\odot\) 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.

Table 1. Model parameters.

| Model          | \(\Delta t_{\text{CBM}}\) (Myr) | \(M_{\text{Eu}}^{\text{CBM}}\) (M_\odot) | Yields from type II SNe |
|----------------|---------------------------------|----------------------------------------|-------------------------|
| Mod1NS         | 10                              | \(10^{-7}\)                              | —                       |
| Mod2NS         | 10                              | \(10^{-7}\)                              | —                       |
| Mod3NS         | 1                               | \(10^{-7}\)                              | —                       |
| Mod1NS'       | 100                             | \(3 \times 10^{-7}\)                    | —                       |
| Mod2NS'       | 10                              | \(3 \times 10^{-7}\)                    | —                       |
| Mod3NS'       | 1                               | \(3 \times 10^{-7}\)                    | —                       |
| Mod1NS”      | 100                             | \(9 \times 10^{-7}\)                    | —                       |
| Mod2NS”      | 10                              | \(9 \times 10^{-7}\)                    | —                       |
| Mod3NS”     | 1                               | \(9 \times 10^{-7}\)                    | —                       |
| Mod1SNNS     | 1                               | \(10^{-7}\)                              | —                       |
| Mod2SNNS     | 10                              | \(2 \times 10^{-7}\)                    | —                       |

\(^{\dagger}\) 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. \(^{\ddagger}\) 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.

3.2 Europium production from core-collapse supernovae

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 [Eu/Fe] versus [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 12–30 M_\odot. In particular, according to Cescutti et al. (2006), a 12 M_\odot star must produce \(M_{\text{Eu}}^{\text{Mod2SN}} = 4.5 \times 10^{-8}\) M_\odot, a 15 M_\odot star, \(M_{\text{Eu}}^{\text{Mod2SN}} = 3.0 \times 10^{-8}\) M_\odot and a 30 M_\odot star, \(M_{\text{Eu}}^{\text{Mod2SN}} = 5.0 \times 10^{-10}\) 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; see Table 1). In particular, from the latter we adopt the yields corresponding to their Model SN2050 (see their Table 2), but for progenitors in the mass range 20–23 M_\odot we assume a constant yield of \(3.8 \times 10^{-8}\) M_\odot rather than a declining yield from \(1.8 \times 10^{-6}\) M_\odot to \(3.8 \times 10^{-8}\) M_\odot, as in the original paper. This assumption is required in order to fit the data, as we will see in the next section.
4 MODEL RESULTS

We run several models with neutron stars as the only Eu source, models with SNeII as the only Eu source as well as models with both sources acting at the same time. We vary the yield from merging neutron stars as well as the time delay for merging and the yields from SNeII. In Table 1 we show the model parameters: in column 1 we report the name of the model, in column 2 the assumed coalescence timescale, in column 3 the assumed yield for CBM and in column 4 the literature source for the assumed yields for SNeII. All models assume the same SFR and the same IMF (see Sect. 2).

In Fig. 1 we show the predicted SNIa and SNIa rates, which are common to all the models, and the predicted CBM rate. As one can see, the CBM rate follows strictly the SNIa rate in shape, although it is smaller in absolute value. In the same figure we report the observed values of the three rates at the present time in the Galaxy and the agreement between model predictions and observations is good.

In Fig. 2 we show the predicted (lines) and observed (symbols) [Eu/Fe] versus [Fe/H] relations: the model predictions refer to the three sets of models with Eu production only from CBM (see Table 1 from Mod1NS to Mod3NS}). The data are a large compilation including the most recent ones. It is clear from this figure that if \( \Delta t_{\text{CBM}} \gtrsim 10 \) Myr the CBM cannot explain the [Eu/Fe] ratios at low [Fe/H]. In any case, even if the minimum value for \( \Delta t_{\text{CBM}} \) is assumed, i.e. 1 Myr, it is not possible to explain the observed points at [Fe/H]< -3.5 dex. This suggests that another Eu source should be active on very short timescales, such as SNeII of high mass (up to 50 \( M_\odot \)). Moreover, if the CBM are the only source of Eu, then the best yield should be \( 3 \times 10^{-7} \) \( M_\odot \), 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 SNe II. 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; model Mod1SN) fits reasonably well the data for [Fe/H] \( \gtrsim -2.0 \) 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] \( \lesssim -3.0 \) dex, we have to reduce the original yields in the 20–23 \( M_\odot \) mass range (see before). In fact, the kink at [Fe/H]~ -3.0 dex in the white curve is related to the appearance of SNeII with progenitors with initial mass \( \sim 20 \) \( M_\odot \). We had to reduce the Eu produced by a \( \sim 20 \) \( M_\odot \) from \( 10^{-9} \) \( M_\odot \) to \( 3.8 \times 10^{-9} \) \( M_\odot \) in order to best fit the data and reduce the kink.

From the comparison of our model predictions with the obser-
vations, 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 to 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 SNeII and CBM. Model Mod1SNNS assumes the SNII yields from Cescutti et al. (2006) and the lowest Eu production from CBM (10−7 M⊙) 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 timescale (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 supernovae from Argast et al. (2004); the adopted Eu yield from CBM is slightly higher than in model Mod1SNNS (2 × 10−7 M⊙), while the coalescence timescale is longer (10 Myr). It is shown that the joint contribution to Eu synthesis from both high-mass SNeII and CBM (whose progenitors are in the range 9–30 M⊙) 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_Eu = 3.5 × 10−10 and X_Fe = 1.34 × 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 a neutron star to be 30 M⊙ 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 neutron star formation in equation (3), namely, 50 M⊙, rather than 30 M⊙. 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 from Cepheids by 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 neutron stars and SNeII. 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 compact binary mergers (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 neutron star system to coalesce and iii) the range of progenitors of neutron stars. 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:

- 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 a 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.

- 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 $10^{-8}–10^{-9}$ $M_\odot$ of Eu per supernova. It is very important to have high stellar masses to produce the Eu observed at very low metallicity.

- 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 a 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 instantaneous mixing approximation (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 adopted again a population synthesis model and a Galactic model like in De Donder & Vanbeveren (2003), reached a conclusion similar to that of the present paper: the CBM can account for the entire r-process production except in the first 100 Myr, but they did not test the case of Eu production from SNeII. More recently, Mennekens & Vanbeveren (2013), adopting 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. 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 neutron stars, and that will be the subject of a forthcoming paper.

ACKNOWLEDGEMENTS

F.M. and D.R. acknowledge financial support from PRIN MIUR 2010–2011, project “The Chemical and Dynamical Evolution of the Milky Way and Local Group Galaxies”, prot. 2010LY5N2T. A.A. aknowledges financial support from PRIN grant 621-2012-4870. S.R. has also been supported by Compstar. Finally, we thank a highly competent referee for his/her careful reading of the manuscript and useful suggestions.

REFERENCES

Arcones A., Janka H.-Th., Scheck L., 2007, A&A, 467, 1227
Arcones A., Thielemann F.-K., 2013, JPhG, 40, 3201
Argast D., Samland M., Thielemann F.-K., Qian Y.-Z., 2004, A&A, 416, 997
Asplund M., Grevesse N., Sauval A. J., Scott, P., 2009, ARA&A, 47, 481
Bauswein A., Goriely S., Janka H.-T., 2013, ApJ, 737, 78
Bensby T., Feltzing S., Lundström I., Ilyin I., 2005, A&A, 433, 185
Belczynski K., Kalogera, V., Bulik, T., 2002, A&A, 372, 407
Brook C. B., Stinson G., Gibson B. K., Shen S., Macciò A. V., Wadsley J., Quinn T., 2013, preprint (arXiv:1306.5766)
Brusadin G., Matteucci F., Romano D., 2001, ApJ, 554, 1044
Cowan J. J., Thielemann F.-K., Truran J. W., 1991, Phys. Rep., 208, 267
De Donder E. & Vanbeveren, D., 2003, NewAstr., 8, 415
Eichler D., Livio M., Piran T., Schramm D.N., 1989, Nature,340, 126
Ekström S., Meynet G., Chiappini C., Hirschi R., Maeder A., 2008, A&A, 489, 685
Fischer T., Whitehouse S. C., Mezzacappa A., Thielemann F.-K., Liebendörfer M., 2010, A&A, 517, 270
Franos P., Depagne E., Hill, V., Spite M., Spite, F., Plez, B., Beers, T. C., Andersen, J. et al., 2007, A&A, 476, 935
Friedel A., 2010, Astronomische Nachrichten, Vol.331, Issue 5, p.474-488
Freiburghaus C., Rosswog S., Thielemann F.-K., 1999, ApJ, 525, L121
Fröhlich U., Hirschi R., Thielemann F.-K., 2012, A&A, 538, L2
Frebel, A., Hix, W. R., Martínez-Pinedo, G., Liebendoerfer, M., Thielemann, F.-K., Bravo, E., Langekan, K., Zinner, N. T., 2006a, NewAR, 50, 496
Frebel, C., Martínez-Pinedo, G., Liebendoerfer, M., Thielemann, F.-K., Bravo, E., Hix, W. R., Langekan, K., Zinner, N. T., 2006b, PhRvL, 96, 2502
Fulbright J., 2000, AJ, 120, 1841
Goriely, S., Bauswein, A., Janka, H.-T., 2011, ApJ, 738, L32
Greggio, L., 2005, A&A, 441, 1055
Greggio L., Renzini A., 1983, A&A, 118, 217
Hirschi R., 2007, A&A, 461, 571
Hirschi R., Meynet G., Maeder A., 2005, A&A, 433, 1013
Hotokezaka K. et al., 2013, PhRvD, 88, 4026
Höpkeohl U., Müller B., Janka H.-T., Marek A., Raffelt G. G., 2010, Phys. Rev. Lett., 104, 251101
Ishimaru Y. & Wanajo, S., 1999, ApJ, 511, L33
Iwamoto K., Brachwitz F., Nomoto K., Kishimoto N., Umeda H., Hix W. R., Thielemann F.-K., 1999, ApJS, 125, 439
Kalogera V., Kim C., Lorimer D. R., Burgay M., D’Amico N., Possenti A., Manchester R. N., Lyne A. G., Joshi B. C., McLaughlin M. A., Kramer M., Sarkissian J. M., Camilo F., 2004, ApJ, 614, L137
Kalogera V., Lorimer D.R: 2000 ApJ, 530, 890
Karakas, A.I., 2010, MNRAS, 403, 1413
Kobayashi C., Umeda H., Nomoto K., Tominaga N., Ohkubo T., 2006, ApJ, 653, 1145
Korobkin O., Rosswog S., Arcones A., Winteler C., 2012, MNRAS, 426, 1940
Kyutoku K., Ioka K., Shibata M., 2013, PhRvD, 88, 1503
Li, W., et al. 2011, MNRAS, 412, 1473
Luck, R. E., Andrievsky, S. M., Kovtyukh, V. V., Gieren, W.; Graczyk, D. 2011, AJ, 142, 51
Lattimer J. M., Mackie F., Ravenhall D. G., Schramm D. N., 1977, ApJ, 213, 225
Lattimer, J.M.& Schramm, D.N., 1974, ApJ, 192, L145
Lattimer, J. M. & Schramm, D. N., 1976, ApJ, 210, 549
Liebendoerfer M., Mezzacappa A., Messer, O. E. B., Martínez-Pinedo G., Hix W. R., Thielemann F.-K., 2003, NuPhA, 719, 144
Martínez-Pinedo G., Fischer T., Lohs A., Huther L., 2012, Phys. Rev. Lett., 109, 251104
Matteucci F., François P., 1989, MNRAS, 239, 885
Matteucci F., Recchi S., 2001, ApJ, 558, 351
Matteucci F., Panagia N., Pipino A., Munnucci F., Recchi S., Della Valle M., 2006, MNRAS, 372, 265
Matteucci F., Spite E., Recchi S., Valiante R., 2009, A&A, 501, 531
Mennekens N., Vanbeveren, D., De Greve, J.P., De Donder, E., 2010, A&A, 515, 89
Mennekens, N. & Vanbeveren 2013 astro-ph/1307.0959, A&A submitted
Meynet G., Maeder A., 2002a, A&A, 381, L25
Meynet G., Maeder A., 2002b, A&A, 390, 561
Micali A., Matteucci F., Romano D., 2013, preprint (arXiv:1309.1283), MNRAS in press
Mishenina, T. V., Gorbaneva, T. I., Orlova, L. F., 2007, Astronomy Reports, Volume 51, Issue 5, p.382
Oechslin, R., Janka, H.-T., Marek, A., 2007, A&A, 467, 395
Peters, P. & Mathews, J., 1964, Phys. Review B, 27, 173001

© 2013 RAS, MNRAS 000, 1–9
This paper has been produced using the Royal Astronomical Society/Blackwell Science \LaTeX{} style file.