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Binary Neutron Stars and Production of Heavy Elements

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Abstract We show how merging neutron stars can be responsible for the production of heavy elements in the solar vicinity, in particular we study the evolution of the abundance of Europium (Eu) relative to iron (Fe), as derived by stellar abundances measured in the Milky Way halo and disk stars. To do that, we adopt a detailed galactic chemical evolution model able to follow the evolution of the abundances of several chemical elements in the gas in our Galaxy. Merging of neutron stars and neutron star and black holes after emission of gravitational waves have been observed for the first time in the event GW170817, which has represented the very first kilonova ever observed in the local universe. The production of heavy elements such as Eu (a typical r-process element) is discussed critically, pointing out that supernovae core-collapse can produce some r-process elements but not enough to explain the solar abundance of Eu. On the other hand, the merging of compact objects can provide an amount of Eu much higher per single event than a single supernova. We discuss the various parameters involved, such as the merging time scales, the fraction of neutron star binaries and the present time rate of kilonova explosions. We compare model results with stellar data and conclude that merging neutron stars can be responsible for the bulk of Eu production

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in the Galaxy under some assumptions: i) the merging binaries should have progenitors in the mass range 9-50$M_{\odot}$, the merging timescales should be as short as 1 Myr and each event should produce $\sim 3 \cdot 10^{-6} M_{\odot}$. We also conclude that the Ligo/Virgo merging neutron star rate is consistent with our chemical evolution model and that if GW170817 is a representative event, then the merging neutron stars can be considered as the main r-process production sites.

Keywords stellar nucleosynthesis · Galaxy: evolution

1 Introduction

The production of s- and r- process elements is not yet completely understood. In particular, it has been suggested that the origin of the r-process elements should be the explosive nucleosynthesis in core-collapse supernovae (SNe), either of low (8-10$M_{\odot}$) or high ($> 20M_{\odot}$) mass (Cowan et al. 1991; Woosley et al. 1994; Wanajo et al. 2001), but many uncertainties are still present in the physical mechanisms involved in r-process element production. In particular, during explosive nucleosynthesis there are too few neutrons to produce heavy elements. An alternative source of r-process elements is the merging of compact objects such as two neutron stars or neutron star and black hole (Freiburghaus et al. 1999; Rosswog et al. 1999;2000; Korobkin et al. 2012). We will focus here on the Eu production by the merging of neutron stars (MNS). We adopt a chemical evolution model for our Galaxy (Chiappini et al. 1997; Romano et al. 2010; Matteucci et al. 2014, hereafter M14) to compute the evolution of Eu as due to the contribution of MNS as well as core-collapse SNe. We will show the results obtained for Eu by M14 plus some new ones obtained by tuning the model on the kilonova rate obtained by the recent Ligo/Virgo measure (Abbott et al. 2017). M14 showed that if each MNS event produces $\sim 3 \cdot 10^{-6} M_{\odot}$ of Eu, the neutron star progenitors lie in the range 9-50 $M_{\odot}$ and the delay time for merging is constant and equal to 1 Myr, the solar abundance of Eu as well as the [Eu/Fe] vs. [Fe/H] relation are well reproduced. In alternative, if some of the three above assumptions are relaxed, a mixture of SN and MNS production can also reproduce the data. The assumed rate of kilonovae in M14 was that suggested by Kalogera et al. (2004), based on binary pulsars (83 Myr^{-1}, although very uncertain).In particular, the SNe should produce Eu mostly at early times thus allowing the time delays for the merging to be longer than 1 Myr and reach also 100 Myr. Komiya et al. (2014) also studied the Eu production in the Milky Way in the framework of hierarchical galaxy formation and using a semi-analytic merger tree. They concluded that for MNS the preferred coalescence timescale has to be 10 Myr and the event rate 100 times larger than currently observed in the Galaxy and that $\sim$ 10% of Eu should be produced by SNe. Vangioni-Flam et al. (2015) computed the cosmic chemical evolution of Eu and concluded that the coalescence time scales should be around 0.1-0.2 Gyr, again allowing also for SN production of Europium. Coté et al. (2018) by means of a chemical model showed that the rates of MNS required to reproduce Eu in the Milky Way are consistent with the Ligo/Virgo rate.

2 The neutron star merger prescriptions

Following the calculations of Korobkin et al. (2012) we assumed that two merging neutron stars of masses $1.4M_{\odot}$ can eject $\sim (10^{-3} - 10^{-2})M_{\odot}$ in the form of heavy elements and a fraction of $\sim (10^{-7} - 10^{-5})M_{\odot}$ is in the form of Europium. From the event GW170817 a mass of Eu of $\sim (3-5) \cdot 10^{-6}M_{\odot}$ has been estimated (Evans et al. 2017; Tanvir et al. 2017; Troja et al. 2017). Concerning the coalescence timescales, we considered three cases with a fixed value: 1 Myr, 10 Myr, 100 Myr. In principle, the coalescence timescale would depend on the original separation of the system, a, and it should behave as $t_c \propto a^4$ but many uncertainties are still present, such as the effects of the common envelope process during binary evolution. In order to compute the rate of merging neutron stars, we assumed that this rate is a fraction of the formation rate of neutron stars following the death of massive stars. We assumed a mass range for the progenitors of neutron stars between 9 and 50 $M_{\odot}$. The fraction of merging binary neutron stars, was fixed by reproducing the Kalogera et al. (2004) rate in M14 and the Ligo/Virgo rate (Abbott et al. 2017) in this paper. The Kalogera et al. (2004) rate is:

$$R_{MNS} = 83^{+209}_{-66.1} Myr^{-1}, \tag{1}$$

while the Ligo/Virgo rate is:

$$R_{MNS} = 154^{+320}_{-122} Myr^{-1}. \tag{2}$$

The derived fraction is $\alpha = 0.018$ in the case of Kalogera's rate and $\alpha = 0.036$ for the Ligo/Virgo rate. It is interesting to note that, by integrating the predicted rate of MNS until the present time (13.7 Gyr) in the Galaxy, we obtain a number of gravitational wave emission events of $\sim (3-6) \cdot 10^6$ in the case of Kalogera and Ligo/Virgo, respectively.

The adopted chemical evolution model reproduces the present time rate of core-collapse SNe (II, Ib, Ic) as well as the rate of Type Ia SNe, deriving from white dwarfs in binary systems (see M14 for all the details on modeling chemical evolution). By means of this model, which follows in detail the evolution of 31 chemical species, we tested whether MNS can reproduce the solar abundance of Eu as well as its behaviour as a function of Fe ([Eu/Fe] vs. [Fe/H]). We compared our model predictions with stellar data in the halo and disk, as we will show in the next paragraphs.

3 Main results: average behaviour

In Figure 1 we show our best model obtained with the prescriptions described above and the local rate of MNS derived by Ligo/Virgo (Abbott et al. 2017).

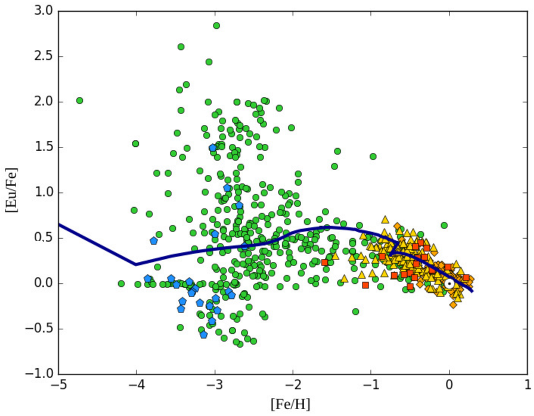

Fig. 1 The [Eu/Fe] vs.[Fe/H] relation predicted and observed in stars of the solar vicinity. The Eu is produced only by MNS with a fixed coalescence time of 1 Myr. The progenitors of the neutron stars are in the range 9-50$M_{\odot}$ and the Eu produced in one event is $3 \cdot 10^{-6} M_{\odot}$. The only difference with the model of M14 is that we tuned the fraction of binary systems giving rise to MNS with the Ligo/Virgo rate (see text). Data: green circles from Frebel (2010); yellow triangles from Reddy et al. (2006); orange rombs from Mishenina et al. (2007); red squares from Ramya et al. (2012); blue pentagons from Fran3C 279 cois et al. (2007).

We obtained the curve by assuming a mass of Eu produced by a single MNS event of $M_{Eu} = 2 \cdot 10^{-6} M_{\odot}$, well inside the suggested range by Korobkin et al. (2012) and very similar to what obtained by M14 by adopting the Kalogera rate as a reference.The model reproduces also the solar abundance of Eu, in particular we predict $X_{EuSun} = 4.2 \cdot 10^{-10}$, with the observed one being $3.5 \cdot 10^{-10}$ (Asplund et al. 2009). If the range of progenitors of neutron stars would be reduced to 9-30$M_{\odot}$ then we should include core-collapse SNe to explain the data at very low [Fe/H], as discussed in M14 and Cescutti et al.(2015). Moreover, our model predicts the average behaviour of the [Eu/Fe] ratio and it is not able to reproduce the observed spread of the data present mainly at low metallicities.

4 Main results: spread in the halo stars

In Figure 3 we show the results of Cescutti et al.(2015) obtained with a model similar to the one of M14 but allowing for inhomogeneous mixing in the early halo phase of the evolution of the Milky Way. In fact, the X-axis respresents only the halo phase where the maximum spread in the [Eu/Fe] ratio in stars is found. The model assumes incomplete mixing in the first stages of Galaxy evolution. The halo of the Milky Way is divided in non-interacting regions with a radius of 90pc and in each region stars form by means of a random function weighted on the assumed IMF (Scalo, 1986). Here, the most metal poor stars are not well reproduced and this suggests that SNe core-collapse at early times

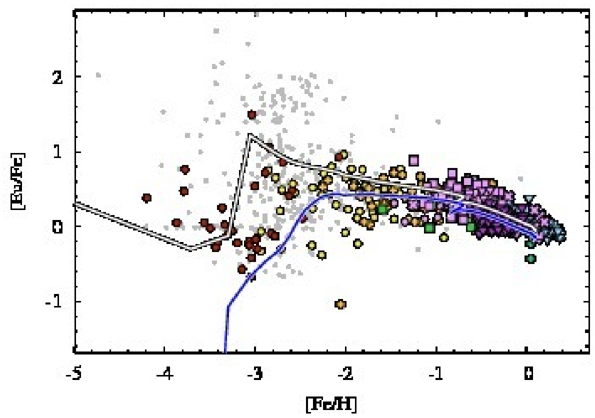

Fig. 2 The [Eu/Fe] vs.[Fe/H] relation predicted and observed in stars of the Milky Way halo. The models shown are those from M14. One is similar to that of Figure 1 while the other is a model with Eu production from core-collapse SNe with masses 20-50$M_{\odot}$ and merging neutron stars with neutron star progenitors in the range 9-30$M_{\odot}$ and coalescence times of the order of 100 Myr. The Eu from one event is $2 \cdot 10{-}6 M_{\odot}$. Models and data from M14.

should have contributed to Eu production. In this case, a longer coalescence time scale can be assumed. In Figure 4 we show the case where we considered the contribution of magneto-rotationally driven supernovae (Winteler et al. 2012) producing Eu only at low metallicity ($Z < 10^{-3}$) and a coalescence time scale costant and equal to 100 Myr. Here all the stars at low metallicity can be reproduced. It should be noted that the contribution of MNS to Eu production, although lower than in the case of only MNS producing Eu, is dominant also in this case.

5 Conclusions

Our main conclusions can be summerized as follows:

- Europium production only from MNS can reproduce the evolution of Eu abundance as well as its solar value if: i) the neutron star systems explode with a gravitational delay no longer than 1 Myr and each event produces $M_{Eu} = 3 \cdot 10^{-6} M_{\odot}$ of Eu, and all stars with masses in the range $9 - 50 M_{\odot}$ leave a neutron star as a remnant.
- An alternative situation suggests that both SNe II and merging neutron stars can produce Eu. The best model in this case assumes that merging neutron stars produce $M_{Eu} = 2 \cdot 10^{-6} M_{\odot}$ and the delay times can be various. The SNe II should produce Eu in a range 20-50 $M_{\odot}$, but the production from merging neutron stars should be predominant.
- The merging neutron star rate derived by Ligo/Virgo is consistent with a chemical evolution model which explains Eu in the Milky Way. Also the derived heavy element production is consistent with chemical models

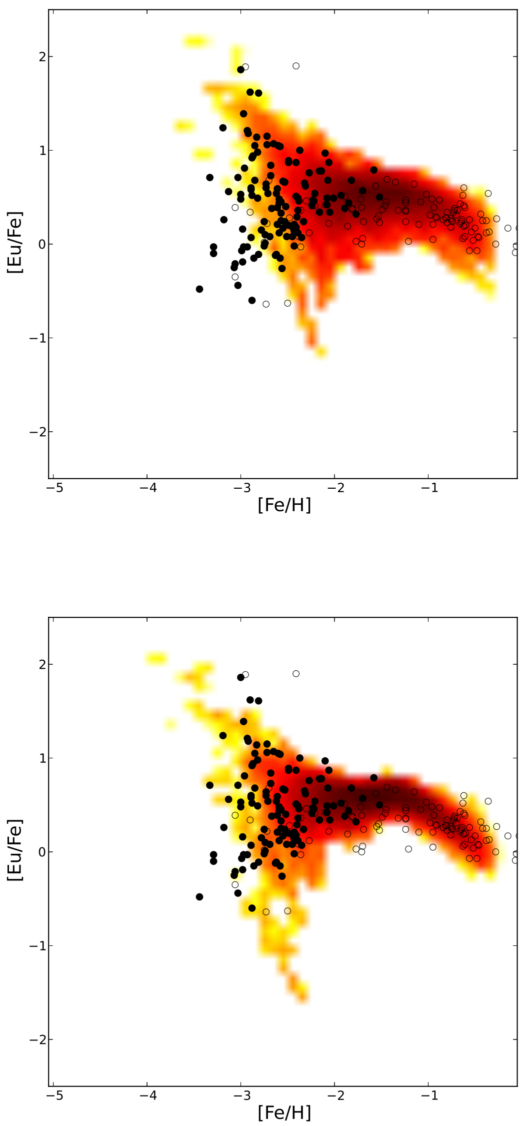

Fig. 3 Upper panel: the [Eu/Fe] vs.[Fe/H] relation predicted and observed in stars of the Milky Way halo. The model prescriptions for Eu production are the same as in the model of Figure 1 but the model allows for inhomogeneous mixing as described in Cescutti et al. (2015). Data are from Frebel (2010) (open and filled circles). Our model predictions are represented by the colored area. Lower panel: the model prescriptions for Eu production assumes a lower yield for Eu per merging event and 100 Myr fixed delay plus the contribution of magneto-rotationally driven SNe. Figure from Cescutti et al. (2015)

(see also Coté et al. 2018). If GW170817 is a representative event, then the merging neutron star process can be considered as the main r-process element site.

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