# The $r$-process and $\nu p$-process in CCSNe, collapsars, hypernovae and mergers, and their effect on galactic chemical evolution

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**Abstract.** In spite of many years of effort, some aspects of the origin and evolution of heavy elements in nature are yet to be understood. Here, we overview the current status of models for the formation of both $r$-process and $\nu p$-process elements. We summarize recent state-of the art developments of supernova and binary neutron star evolution in both $r$-process and $\nu p$-process nucleosynthesis. In particular, we highlight two recent recent works detailing the emerging evidence for the important role of hypernovae (energetic supernovae) and collapsars (jets from the collapse of massive stars to a black hole). These studies illuminate how such events may play a key role in the origin and early explosive nucleosynthesis and evolution of some heavy-elements.

Here, we summarize two recent papers [1, 2] that highlight the important roles of collapsars and hypernovae for the formation of both $r$-process [1] and $\nu p$-process isotopes [2]. In the former work we summarized recent state-of-the-art developments in supernova and binary neutron-star evolution regarding the evolution of $r$-process elements. In particular, we examine the important role of collapsar jets from the collapse of massive stars to a black hole) in the early evolution of the $r$-process abundances. In the second work we highlight recent emerging evidence for the important role of hypernovae (energetic supernovae) in the early evolution of some of the isotopes formed by the $\nu p$-process.

## 1. Collapsars and the $r$-process

The astrophysical site for rapid-neutron-capture nucleosynthesis (the r-process) remains an active area of research [3]. The neutrino-driven wind (NDW) of core-collapse supernovae (CCSNe) may only produce light r-process elements [4]. Another source, is the jet driven by magneto-hydrodynamics (MHDJ) from fast rotating, CCSNe with high magnetic fields [5]. In addition, it is a current view by some [6, 7] that neutron-star mergers are the main contributor to r-process nucleosynthesis in the Galaxy. This line of thought can be traced to the LIGO/VIRGO detection of gravitational waves (event GW170817) from a merging binary neutron-star system (NSM) along with a coincident gamma-ray kilonova GRB170817A [8, 9]. It has been suggested that the opacity of the light curve of the expanding ejecta may be due to presence of heavy elements (see, however, [10]). There are also observations [11, 12] suggesting that there was massive ejection of r-process material into the dwarf galaxy Reticulum II without an expected large amount of supernova ejecta enrichment.

In Ref. [1] it was argued that the contribution from massive stars collapsing to a black hole (collapsars) may also be a viable site for the main r-process abundances [13]. Previously, in Ref. [14] evidence for an additional production site was identified for the r-process that contributed in the early Galaxy but ceased at higher metallicity. This was necessary to account for the decrease of the r-process elements as the iron abundance increased after the ignition of Type Ia supernovae (at [Fe/H] $\sim -1$). In [1] we suggested that this source was collapsars. The galactic chemical evolution (GCE) of r-process abundances experiencing a range of astrophysical sites and possible conditions was explored. That paper argued that collapsars are indeed the desired source. It was also emphasized that, even in the most optimistic of circumstances, the NSMs could only contribute a negligible fraction of the r-process abundances in the present solar-system.

The reason that NSMs are suppressed is an unavoidable time delay from the time of star formation to the merger and ejection of r-process material. Even with a timescale for mergers as small as $\sim 10^6$ yr, neutron star binaries are formed a with a distribution of merger time scales due to the distribution of separation distances of the initial binary. This delay limits the amount or possible NSM contribution to the solar-system abundances. It has been pointed out, however, [15] that merging dwarf galaxies may have contributions from NSMs due to their slow stellar nucleosynthesis enrichment timescale.

Both collapsars and SNe are the result of the collapse of a massive star at the end of their lifetime. They can easily cause the build up r-process isotopes in the early Galactic disk. However, NSMs require the merger of the remnants of massive stars. The occurrence rate is $\sim 0.1 - 1\%$ of the observed SN rate in the Galaxy. The orbital dynamics of observed binary pulsars suggest coalescence times ranging from $\sim 10^8$ to more than $10^{10}$ yr [16].

The universality [17] of the observed abundance pattern of intermediate mass $40 < Z < 80$ elements in metal-poor halo stars of the Galactic Halo and in the solar system has been invoked as evidence that only a single site has contributed to the early r-process abundances [18, 19, 6, 20, 14]. However, in [1] it was demonstrated that the elemental abundances can exhibit universality even when the isotopic abundances are not similar [21, 22, 13]. In particular, the relative contributions of multiple r-process models (collapsars, CCSNe, and NSMs ) were examined along with their associated galactic chemical evolution (GCE). This was based upon the well tested model of [23] that was modified to include various r-process source abundance contributions. This model produces a star formation rate similar to that observed [24] and also reproduces the chemical evolution of light elements from hydrogen to zinc [23]. The gas evolution involves a cycle of star formation, stellar evolution and nucleosynthesis; ejection of material into the interstellar medium (ISM); mixing of ejecta with the ISM; and formation of the next generations of stars. An exponentially declining galactic inflow rate with timescale of 4 billion years was adopted in [1]. This is consistent with the hierarchical clustering paradigm.

A large parameter space of nuclear physics input, and astrophysical models was employed to study the general evolution of r-process abundances. It was concluded that CCSNe and collapsars were the most important early contributors to r-process abundances in the Galaxy. On the other hand, NSMs only contributed after the iron was already enriched to [Fe/H]$> -1$. Moreover, this conclusion was true even for a relatively short time for binary neutron-stars to merge. The observed lower limit to the NSM timescale is $\sim$50 My [16]. However, coalesce times of $\tau_{\rm g} = 1$, 10 and 100 My were also considered. Although, the merger of dwarf galaxies may provide some r-process enriched stars, most of the gas arriving from the intergalactic medium is depleted in r-process abundances [25].

As the r-process occurs it eventually terminates by either beta-decay induced fission or neutron induced fission [21] Thus, the fission fragment distribution (FFD) also impacts the r-process abundance curve. In [1] the impact of both symmetric fission and asymmetric fragment distributions were explored. It was found that the FFD affects abundances in the vicinity of r-process peaks. Models were also run with and without the contribution from collapsars.

In Ref. [1] it was concluded that among the possible astrophysical sites, CCSNe, i.e. NDW and MHDJ and collapsars, are the main contributor during the early Galaxy. The contribution from NSMs, on the other hand, grows with increasing metallicity and only achieves an abundance that is about 1 % of the total r-process abundance of solar elements. This conclusion remains true for a wide range of minimum merger times $\tau_g$ = 1 - 100 My in any GCE models including multiple sites and different input nuclear physics. The elemental abundance was also calculated in Ref. [1]. It was concluded that even with the diverse time-dependent contributions from various $r$-process sources, the observed universality of the r-process elemental abundance pattern [17] still emerges.

## 2. Hypernovae and the $\nu p$-process

The proton-rich $p$-nuclei cannot be synthesized through the $r$- or $s$-process. A popular model for $p$-nuclei is production by successive ($p$, $\gamma$) or ($\gamma$, $p$) reactions [26, 27, 28] on heavier isotopes in a high temperature environment (the $\gamma$-process). However, the $\gamma$-process does not explain the relatively large abundances of $^{92,94}$Mo and $^{96,98}$Ru. In Ref. [29] the $\nu p$-process scenario was introduced. In this process, free neutrons produced via $p(\bar{\nu}_e,\ e^+)n$ reactions in a proton-rich neutrino-driven wind of CCSNe enhancesthe production of $^{92,94}$Mo and $^{96,98}$Ru. However, observational evidence of these processes occurring in the Galaxy has been sparse.

However, in Ref. [2] we investigated the GCE of Mo and Ru produced in the $\nu p$-process. The yields of $^{92,94}$Mo and $^{96,98}$Ru produced in the $\nu p$-process in both SNe II and hypernovae (HNe) were included. This work concluded that the operation of the $\nu p$-process in hypernovae best explains the enhanced abundances of Mo and Ru observed in metal-poor stars of the Galactic Halo.

In these models, [2] the $\nu p$-process isotopes were produced in the late ($t > 1$s) times after the explosion. Nucleosynthesis occurrs within a general-relativistic, spherically symmetric neutrino driven wind [30] calibrated to 3D core-collapse SN simulations of Refs. [31, 32]. The models for neutrino-driven winds in hypernovae were taken from the $100 M_\odot$ progenitor star of Ref. [33]. In this scenario, a proto-neutron star with large mass ($\sim 3 M_\odot$) survives for a few seconds before it collapses to a black hole. The final yields of $p$-nuclei were obtained from the product of the PNS lifetime ($\approx$ 1 s) times the rate of mass ejection ($\dot{M}$) and the mass fraction ($X_i$) of $p$-nuclei in the ejecta..

There are seven stable isotopes of molybdenum. Only $^{92}$Mo and $^{94}$Mo are considered $p$-nuclei while $^{96}$Mo is only produced in the $s$-process. The other isotopes have contributions from both the $s$- and $r$-processes. The origin of Ru is similar to Mo. The isotopes $^{96}$Ru and $^{98}$Ru are deemed to be $p$-nuclei, while $^{100}$Ru is only produced in the $s$-process. The other Ru isotopes are synthesized by both the $s$-process and $r$-process. The GCE calculations for the $p$-nuclei in [2] utilized the same model described in the previous section [1, 23].

The SN production rate of each $p$-nucleus was derived from the event rate of CCSNe (including hypernovae) and the ejected mass of newly synthesized $p$-nucleus. The stellar initial mass function was taken from Kroupa [34] and the mass range of SNe and HNe progenitors stars was taken to be $8-60 M_\odot$ and $60-100 M_\odot$, respectively. For these parameters, 4% of massive stars explode as hypernovae. This is consistent with observations. The $\gamma$-process yields were taken from the models of [35] for SNe Ia and from [36] for CCSNe. The contributions from SNe Ia for $p$-nuclei were taken from [35] based upon their Case A1. The production of the $\gamma$-process isotopes from CCSNe utilized yields from the *xi45* model of the KEPLER simulations [36].

The models of Ref. [2] showed that the $\gamma$-process and $\nu p$-process from supernovae alone could not explain the evolution of the Mo abundance in the metallicity range up to [Fe/H] < -1. The contribution of the $s$-process to the Mo and Ru abundances is also negligibly small.

In contrast, however, the $r$-process makes a relatively large contribution when [Fe/H] < -1. However, the amount of $r$-elements is somewhat below the observed stellar ratios. The $\nu p$-process contribution from HNe significantly increased the abundance of the $p$-isotopes. In particular, for [Fe/H] $< -2$, the production by the $\nu p$-process from hypernovae is larger than that of the $r$-process. Thus, hypernovae are the main contributor to the $\nu p$-process at low metallicity, [Fe/H]$< -2$. These results confirm that the observed Mo abundances in the low metallicity stars of the Galactic Halo are mainly formed via the $\nu p$-process in HNe. Because massive $\sim 100 M_{\odot}$ [37] population III stars are present in the early Galaxy, the conclusion that hypernovae are the main contributor at low metallicity region is reasonable.

Regarding Ru, the $\gamma$-process and the $\nu p$-process in normal CCSNe do not contribute to the elemental abundances of Ru. However, the $\nu p$-process in hypernovae increases the elemental abundance at low metallicity, although not as much as for Mo. This is because the solar isotopic percentage of the $p$-isotopes $^{92,94}$Mo is as much as 24.1%, while that of Ru ($^{96,98}$Ru) is only 7.4%. The abundance of $^{92,94}$Mo might also be produced in moderately neutron-rich ejecta ($Y_e \sim 0.47$) [38, 39]. If such an early neutron-rich ejecta were taken into account, the total abundances of Mo and Ru could increase in the GCE calculation and the model prediction could be more in line with observed stellar abundances.

In summary, it has been shown in [2] that the $\nu p$-process in neutrino-driven winds of hypernovae contribute substantially to the GCE of $^{92,94}$Mo and $^{96,98}$Ru, while the contribution from the $\nu p$-process in ordinary CCSNe is negligible. Moreover, the hypernova $\nu p$-process contribution to the evolution of $p$-nuclei is largest at low metallicity. Indeed, the observed high [Mo/Fe] ratios for metal-poor stars confirm that, indeed, the $\nu p$-process in hypernovae is the main contributor to $^{92,94}$Mo and $^{96,98}$Ru in the Galaxy.

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## References

[1] Yamazaki Y, He Z, Kajino T, Mathews G J, Famiano M A, Tang X and Shi J 2022 *Astrophys. J.* **933** 112
[2] Sasaki H, Yamazaki Y, Kajino T, Kusakabe M, Hayakawa T, Cheoun M K, Ko H and Mathews G J 2022 *Astrophys. J.* **924** 29
[3] Kajino T, Aoki W, Balantekin A, Diehl R, Famiano M and Mathews G 2019 *Prog. Part Nucl. Phys.* **107** 109 – 166 ISSN 0146-6410
[4] Wanajo S 2013 *Astrophys. J. Letters* **770** L22
[5] Winteler C, Kaeppeli R, Perego A, Arcones A, Vasset N, Nishimura N, Liebendoerfer M and Thielemann F K 2012 *Astrophys. J. letters* **750** L22
[6] Hotokezaka K, Beniamini P and Piran T 2018 *Int. J. Mod. Phys. D* **27** 1842005
[7] Frebel A 2018 *Ann. Rev. Nucl. Part. Sci.* **68** 237–269
[8] Abbott B P, Abbott R, Abbott T, Acernese F, Ackley K, Adams C, Adams T, Addesso P, Adhikari R, Adya V *et al.* 2017 *Physical Review Letters* **119** 161101
[9] Abbott B P, Abbott R, Abbott T D, Acernese F, Ackley K, Adams C, Adams T, Addesso P, Adhikari R X, Adya V B and Others 2017 *Astrophys. J. Letters* **848** L13
[10] Domoto N, Tanaka M, Wanajo S and Kawaguchi K 2023 *IAU Symposium* **363** 237–240
[11] Ji A P, Frebel A, Simon J D and Chiti A 2016 *Astrophys. J.* **830** 93
[12] Roederer I U, Sneden C, Lawler J E, Sobeck J S, Cowan J J and Boesgaard A M 2018 *Astrophys. J.* **860** 125
[13] Siegel D M, Barnes J and Metzger B D 2019 *Nature* **569** 241–244
[14] Côté B, Fryer C L, Belczynski K, Korobkin O, Chruślińska M, Vassh N, Mumpower M R, Lippuner J, Sprouse T M, Surman R and Others 2018 *Astrophys. J.* **855** 99
[15] Hirai Y, Ishimaru Y, Saitoh T R, Fujii M S, Hidaka J and Kajino T 2015 *ApJ* **814** 41 (*Preprint* `1509.08934`)

[16] Swiggum J K, Rosen R, McLaughlin M A, Lorimer D R, Heatherly S, Lynch R, Scoles S, Hockett T, Filik E, Marlowe J A and Others 2015 *Astrophys. J.* **805** 156

[17] Sneden C, Cowan J J and Gallino R 2008 *Annu. Rev. Astron. Astrophys.* **46** 241–288

[18] Mathews G, Bazan G and Cowan J 1992 *Astrophys. J.* **391** 719–735

[19] Argast D, Samland M, Thielemann F K and Qian Y Z 2004 *Astronomy & Astrophysics* **416** 997–1011

[20] Ishimaru Y, Wanajo S, Aoki W, Ryan S G and Prantzos N 2005 *Nuclear Physics A* **758** 603–606

[21] Shibagaki S, Kajino T, Mathews G J, Chiba S, Nishimura S and Lorusso G 2016 *Astrophys. J.* **816** 79

[22] Suzuki T, Shibagaki S, Yoshida T, Kajino T and Otsuka T 2018 *Astrophys. J.* **859** 133

[23] Timmes F X, Woosley S E and Weaver T A 1995 *Astrophys. J. Supplement Series* **98** 617–658

[24] Madau P and Dickinson M 2014 *Ann. Rev. Astr. Astrop.* **52** 415–486

[25] Péroux C and Howk J C 2020 *Ann. Rev. Astr. Astrop.* **58** 363–406

[26] Burbidge E M, Burbidge G R, Fowler W A and Hoyle F 1957 *Reviews of Modern Physics* **29** 547–650

[27] Woosley S E and Howard W M 1978 *Astrophys. J. Suppl.* **36** 285–304

[28] Hayakawa T, Iwamoto N, Kajino T, Shizuma T, Umeda H and Nomoto K 2008 *Astrophys. J.* **685** 1089–1102

[29] Fröhlich C, Martínez-Pinedo G, Liebendörfer M, Thielemann F K, Bravo E, Hix W R, Langanke K and Zinner N T 2006 *Phys. Rev. Lett.* **96** 142502

[30] Otsuki K, Tagoshi H, Kajino T and Wanajo S y 2000 *Astrophys. J.* **533** 424–439

[31] Burrows A, Radice D, Vartanyan D, Nagakura H, Skinner M A and Dolence J C 2020 *MNRAS* **491** 2715–2735

[32] Nagakura H, Burrows A, Vartanyan D and Radice D 2021 *MNRAS* **500** 696–717

[33] Fujibayashi S, Yoshida T and Sekiguchi Y 2015 *Astrophys. J.* **810** 115

[34] Kroupa P 2001 *Monthly Notices of the Royal Astronomical Society* **322** 231–246

[35] Kusakabe M, Iwamoto N and Nomoto K 2011 *Astrophys. J.* **726** 25

[36] Travaglio C, Rauscher T, Heger A, Pignatari M and West C 2018 *Astrophys. J.* **854** 18

[37] Hirano S, Hosokawa T, Yoshida N, Umeda H, Omukai K, Chiaki G and Yorke H W 2014 *Astrophys. J.* **781** 60

[38] Bliss J, Arcones A and Qian Y Z 2018 *Astrophys. J.* **866** 105

[39] Wanajo S, Müller B, Janka H T and Heger A 2018 *Astrophys. J.* **852** 40