

Could failed supernovae explain the high *r*-process abundances in some low metallicity stars?

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(Received September 16, 2019)

Rapid neutron capture process (*r*-process) elements have been detected in a large number of metal-poor halo stars. The observed large abundance scatter in these stars suggests that *r*-process elements have been produced in a site that is rare compared to core-collapse supernovae (CCSNe). Although being rare, neutron star mergers (NSM) alone have difficulties explaining the observations, especially at low metallicities. In this paper, we present a complementary scenario: Using black hole - neutron star mergers (BHNSMs) as additional *r*-process site. We show that both sites together are able to explain the observed *r*-process abundances in the Galaxy.

KEYWORDS: Galactic chemical evolution, *r*-process, low metallicity stars

1. Introduction

The *r*-process (e.g., [1,2], and references therein) is a nuclear process of major importance for the formation of the heaviest elements. At present, the site of this process is still not yet unambiguously identified (e.g., [3]). Although it has been shown that neutron star mergers (NSMs) are able to produce *r*-process elements [4], it is yet unclear whether it is the *exclusive r*-process site [5–7]. For a NSM, two neutron stars (NSs) are required. Consequently, two CCSNe must have occurred that produced these two NSs. These CCSNe eject iron (Fe) and other metals into the interstellar medium and increase its metallicity. This means that the two NSs merge in an environment that has already been polluted by at least two CCSNe. Very metal-poor stars with high *r*-process enrichment (e.g., [8]) are challenging to be explained within these conditions.

In this work, we discuss the impact of black hole - neutron star mergers (BHNSMs) as additional *r*-process site.

2. The model

We use the inhomogeneous Galactic chemical evolution code “ICE” [9] to simulate the evolution of the elements in the Galaxy. We model a gas box with an edge length of 2kpc, with a resolution of 20pc. Parametric gas inflows, detailed star formation and death prescriptions, and gas movement in three dimensions are included. A detailed description of the model can be found in [6]. Here we only highlight few details:

2.1 Stars

Low- and intermediate-mass stars (with zero age main sequence mass, ZAMS, of $m < 8M_{\odot}$) are not expected to contribute significantly to the elements targeted in this work, so their main impact in this model is to lock up gas during their life time. Massive stars ($ZAMS \geq 8M_{\odot}$) go through all burning stages until they reach the end of their life time. We then use the results of the explosion energy predictions of the CCSN simulation suite PUSH [10–13] in order to determine whether a massive star dies in a CCSN explosion (under the ejection of metals, leaving behind a NS), or the explosion fails and the star collapses to a black hole (BH) instead.

2.2 Compact binary mergers

When a massive star is born, there is a chance that it has a massive star as companion. After both stars have died, they both leave compact objects behind (either a NS or a BH, see [9–13] for the criteria), so that there is the possibility that these two objects eventually merge. We estimate that $P_{r\text{-proc}} = 4\%$ of all newly born massive stars will have a companion in the relevant mass range ($8M_{\odot} \leq m \leq 50M_{\odot}$) and will end in a system that performs a NSM or BHNSM after both stars have died and the two compact objects (two NSs or one NS and one BH) have lost enough angular momentum (due to the emission of gravitational waves) to merge. Following the method described in [14], the chosen value of $P_{r\text{-proc}}$ would translate to a gravitational wave rate of $\approx 1800 \text{ Gpc}^{-3} \text{ yr}^{-1}$, which is well within the rate predicted by the LIGO gravitational wave observations from NSMs ($1540_{-1220}^{+3200} \text{ Gpc}^{-3} \text{ yr}^{-1}$ [15, 16]).

3. Results and discussion

It has been shown in [5–7, 17, 18] that NSMs acting as *exclusive* r -process production site have difficulties explaining the high abundances in r -process elements in some low metallicity stars. This is due to the fact that *two* neutron stars are required for this site. Consequently, the r -process element production can only occur in an environment that has been enriched in metals at least *twice*. Once BHNSMs are added to serve as a second r -process element production site into our model, both sites together are able to explain the observed abundances (see fig. 1). Two major reasons have been identified why adding BHNSMs as second r -process element production site cures the deficiencies of NSMs acting as exclusive r -process site:

- (1) BHNSMs only require *one* NS, so only *one* previous CCSN must have occurred before the r -process production event. This enables r -process elements to be produced in an environment with lower metallicity in comparison to NSMs (see left panel of fig. 2 for illustration).
- (2) When some stars die in a failed supernova, they do not contribute metals to the Galactic inventory. This means that less stars eject metals in a given amount of time to the Galactic inventory. Consequently, the increase of metallicity with age is slower compared to a model where all stars die in a CCSN explosion (see right panel of fig. 2).

The following caveats should be noted in conjunction with the results:

- (1) Regular CCSNe were not included in this model as r -process sources, although there is a chance of r -process element production from special sub-classes of CCSNe (e.g., [19]).

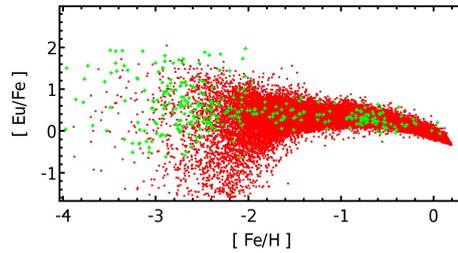


Fig. 1. Model stars (Red dots) when BHNSMs act as additional r -process site. Green stars represent observations. Europium (eu) is used as a proxy for r -process elements

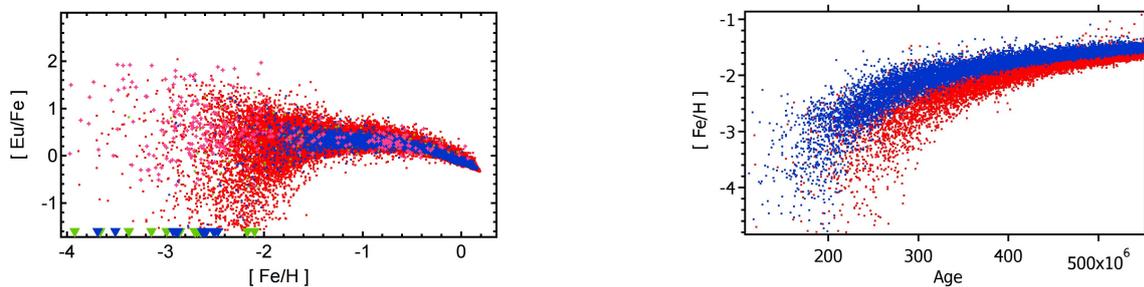


Fig. 2. Left panel: Locations of BHNSMs (green dots/triangles) and NSMs (blue dots/triangles) in the $[\text{Eu}/\text{Fe}]$ vs. $[\text{Fe}/\text{H}]$ plane, whereas red dots represent all model stars. Figure taken from [9]. Right panel: Illustration of a shifted age-metallicity relation. Red (blue) squares represent model stars in a model that does (not) permit failed SNe. A model that permits failed SNe produces less Fe during a given time step, so the $[\text{Fe}/\text{H}]$ enrichment is slowed down as opposed to a model which does not allow failed SNe.

- (2) We did not consider the contribution of sub-halos (e.g., dwarf galaxies) in this model, which merged at early Galactic stages to build up the Galactic halo. (e.g., [20, 21]). With lower halo mass, the star formation efficiency could be lowered in such sub-halos, reducing the importance of the delay times for two compact objects to merge [22]. However, the relation of the halo mass vs. star formation efficiency is poorly constrained at the low mass end, leaving this scenario with high uncertainties [23].
- (3) The rates for compact binary mergers are chosen relatively high, but still in good agreement with observations (see section 2).
- (4) We note that realistically, delay time *distributions* have to be employed for the inspiral of two compact objects, which is not done in our model. This might probably cause issues at the higher end of the metallicity ($[\text{Fe}/\text{H}] \geq -1$, e.g., [14, 24, 25]).
- (5) The coalescence of a NS with a BH could be faster than in a system consisting of two NSs. However, this case is not considered here, as this would probably allow BHNSMs to contribute at even lower metallicities, so the case modelled here would be a lower limit of their contribution.
- (6) We did not consider NS natal kicks in our model.
- (7) Using black holes from failed SNe to merge with a NS might as well end up in the NS being completely swallowed. However, if the BH is on the rather low mass end of the spectrum ($m \leq 10M_{\odot}$) and spinning sufficiently fast, ejection of r -process elements is expected from the merger [26].
- (8) Theoretically, a star might explode in a CCSNe while leaving behind a black hole. The presence of such a sub-class of CCSNe might affect the conclusions drawn in this work; However, for

progenitors in that mass range, it is probable that the fallback will swallow most heavier metals, so the effect on point (2) of the results should only be marginal.

Acknowledgements

This work was supported by a fellowship of the Swiss National Science Foundation (SNF). BW and CF acknowledge support from the Research Corporation for Science Advancement through a Cottrell Scholar Award. CF was partially supported by the United States Department of Energy, Office of Science, Office of Nuclear Physics (award numbers SC0010263 and DE-FG02-02ER41216). FKT was supported by the European Research Council (FP7) under ERC Advanced Grant Agreement No. 321263 - FISH, and the SNF. MP acknowledges the support from the SNF and the ‘ Lendület-2014 ’ Programme of the Hungarian Academy of Sciences (Hungary), of STFC, through the University of Hull Consolidated Grant ST/R000840/1, and access to VIPER, the University of Hull High Performance Computing Facility. BW, BC and MP acknowledge the support from the ERC Consolidator Grant (Hungary) funding scheme (project RADIOSTAR, G.A. n. 724560). BW, CF, BC, and MP acknowledge support of the National Science Foundation (USA) under grant No. PHY-1430152 (JINA Center for the Evolution of the Elements). This article is based upon the work from the ‘ ChETEC ’ COST Action (CA16117), supported by COST (European Cooperation in Science and Technology). We thank the organizers of the OMEG 15 symposium for a successful conference.

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